THE SCIENCES

A SURVEY COURSE FOR COLLEGES

Edited by Gerald Wendt, Ph.D.

PHYSICS

W. F. G. Swann
Bartol Research Foundation of The Franklin Institute

CHEMISTRY

Gerald Wendt

EARTH SCIENCES

J Harlen Bretz
University of Chicago

ASTRONOMY

Clyde Fisher and Marian Lockwood
Hayden Planetarium, American Museum of Natural History

BIOLOGY

Howard M. Parshley
Smith College

THE BODY FUNCTIONS

Ralph W. Gerard
University of Chicago

EARTH SCIENCES

Meteorology, Oceanography, Geology

BY

J HARLEN BRETZ, Ph.D.

PROFESSOR OF GEOLOGY, UNIVERSITY OF CHICAGO

THE SCIENCES

A SURVEY COURSE FOR COLLEGES

EDITED BY

GERALD WENDT, PH.D.

NEW YORK

JOHN WILEY & SONS, Inc.

London: CHAPMAN & HALL, Limited

1940

PRINTED IN U. S. A.

PRESS OF
BRAUNWORTH & CO., INC.
BUILDERS OF BOOKS
BRIDGEPORT, CONN.

THE SCIENCES

EDITOR'S PREFACE TO THE SERIES

Science has many aspects, but above all it is the best use of the human intelligence to improve the conditions under which we live. In order thus to control our environment the first purpose of science must be to study and understand it. This understanding has built civilization, produced our wealth, determined many of our institutions, and has molded even our intimate outlook on life. It has become a powerful social force.

Education, on the other hand, is primarily the adjustment of each individual to his environment, thereby fitting him for a successful place in it and for a happy life. It is the simplest logic, then, to conclude that an understanding of science is an essential element in everyone's education.

Though this truth is not seriously disputed, it is nevertheless seldom that a college curriculum accords with it. The reason lies in that extreme of specialization which alone makes scientific research possible. Courses in science taught by successful specialists have for decades looked primarily toward the professional training of more specialists. This purpose has far outweighed the need of future citizens for a broad understanding of the universe and for learning the best use of the human intelligence. Technical courses in the various sciences have, indeed, long been offered to every student, but they rarely aroused his interest and seldom met his needs.

In recent years numerous efforts have been made to survey science as a whole and to present it as an integral part of a liberal education. It is not difficult to sketch the scene superficially, but the result is a smattering of descriptive knowledge which is far from being science. It is also possible to select important technical phases of each science and to ease their

gravity with a froth of light words. But this too is not enough. The student and the citizen need to absorb the scientific attitude, to master the scientific method of thought, and to understand the basic concepts of the sciences. Only thus, delving beneath the superficial and avoiding the burden of the technical, can they be ready to read further and to understand in the decades to come what science is doing and can do. Only thus can their own intelligence be called into play.

Hence in this series the basis of selection is such understanding. It has been a difficult choice, for each author is keenly aware of great and important topics omitted or scantily treated. Yet condensation is mandatory. Each author in the series is a master of his own subject and each has surveyed his field from this point of view—to present what is most needed for broad understanding, to omit all that is likely to be forgotten in any case, and to prepare the student for life in the second half of the twentieth century.

Each book is an essay in itself, but the books of the series may be combined in any number and in almost any order to form a comprehensive and liberal course in science. Each contains ample suggestions for further reading.

It is apparent that the needs of college students in such a course are no different from those of any intelligent citizen in search of education, or even of college graduates seeking to fill the great gaps left in the curricula of former years. They too have questions that remain unanswered in the light, fantastic books of "popular science" and that are only aggravated by the ponderous technical textbooks. They too need the essential concepts, the method of thought and investigation, and the distinctive intellectual attitude of science.

Thus we hope that this provides the answer—a brief but significant survey of the fundamental sciences, an elementary but sound foundation for the further study, but above all a key to the understanding of our environment and of the possibilities inherent in science.

GERALD WENDT
Editor

PREFACE

This book is about our home, the Earth. Each of us knows a part of it well, though only on the surface. We in this book shall go below the surface in a different sense—beneath the description of the scenes and events to an understanding of their causes. The weather, the course of the rivers, the salt of the sea, the mountains and earthquakes do not just happen. Many of us have seen the landscape without understanding, and so have missed much of the fun of being intelligently alive.

The rise of mankind from savagery has required us to understand "Nature" and to master our original hostile environment. We now live fairly harmoniously with nature. We have done this by finding all the facts possible, by looking for relations between them, by using rigorous logic in reaching conclusions, and by refusing to mix wishing with thinking. This alone is responsible for our command over nature. And this same method of seeking the unchangeable causes and their inescapable effects alone will solve the still greater problem of harmonious relations among men.

Another title for this book might have been "Our Terrestrial Environment." Constant endeavor has been made, in presenting the conclusions and interpretations herein contained, to approach them as the problems they once were, to ask the questions the first investigators must have asked. More to be desired than a memorization of facts is an appreciation of the method of scientific approach and of its trustworthiness.

The literature of the earth sciences is enormous in each of the major fields. Since this survey can be only an introduction to these fields, other books for the college student and the intelligent non-technical reader are listed. Material in periodical

literature is also listed, as are numerous publications of the United States Government.

Governmental activities go much beyond the regulation of human inter-relations. Many states maintain a geological survey for the service of their citizens. The Federal Government has staffs of very competent scientists in virtually every phase of our contact with the terrestrial environment. Everybody knows of the Weather Bureau's daily forecasts. Its service to aviation, its hurricane warnings, and its river flood reports (warnings to those farther downstream) are less well known. The Iceberg Patrol in the North Atlantic was born of the mid-ocean sinking of the *Titanic* from collision with an iceberg on her maiden voyage. Coast charts for navigation are surveyed and constantly revised by the Coast and Geodetic Survey. Tide tables are computed and issued annually by the United States Naval Observatory, from which source also we get precise time. The United States Geological Survey makes topographic maps, gauges streams (for navigation, power, irrigation), measures ground-water supplies, reports on the geology of all rocks and minerals for which man finds any conceivable use, and studies the rock record and topographic record of our continent's history. The Soil Conservation Service works on the manifold aspects of that great problem of maintaining our soils after nature's regimen has been upset. All these (and many more) services are reported in the publications of the United States Government Printing Office.

I have to thank hundreds of college undergraduates for an appreciation of many difficulties they encounter in comprehending the phenomena of our terrestrial environment. Endeavoring to reduce these difficulties, I have striven throughout this book to make an inductive approach in logically connected steps and to stand on verified fact when reaching up into the tenuity of theory. I thank one of these students in particular, my own youngster Rudolf, for the excellent original drawings in this book.

UNIVERSITY OF CHICAGO J HARLEN BRETZ
April, 1940.

CONTENTS

EARTH SCIENCES

CHAPTER I

OUR WORLD

WE MEET THE ENVIRONMENT. Bright islands with wooded hills, valley farms and villages! Encircling arms of blue salt water! As the panorama unreeled that sunny afternoon, the bored gentleman on the excursion steamer groaned faintly. "Wish we were back in town," he said. "All you see is just land and water, land and water." He drawled the last words in disgust. One of the group, to soothe him, remarked on the distant view. He looked wearily in the direction indicated, across ten miles of sunlit sea to the mainland where, forty miles away, a snow-clad mountain on the horizon rose fourteen thousand feet into the air. "Oh yeah, sure enough," he said. "Usually hidden by clouds, isn't it?" His attention shifted to the problem of finding a shady place for his chair.

What a planet! Just land and water, and air as an afterthought. The water beneath him was salty. He knew that. So did the Jersey cows pasturing along the island beach. These long, tortuous inlets; fingers of the ocean thrust into, and clutching the edge of, the continent! They afforded steamer routes and fishing grounds. What other interest could they have? These islands, part of the clutching of that active sea onto the passive land! They offered lumber, and, after that was gone, farm sites. Perhaps their bedrock was worth quarrying, possibly it contained ore deposits. Yes, they were undeniably pretty in the sunlight. But what other appeal could islands have?

The ship's officers could have told him the inlet water was as deep as the island hills were high, that the islands stood waist deep in the sea—if he had asked. The broad, yellow beaches bordering the islands had long piers flung across them to reach steamer depth at low tide. Tide? Why tides? Why tides in the salt water, but none (as he well knew) in the big inland fresh-water lake twenty miles away? Why is the sea water salty? Cows never will puzzle about that. Lovely weather today! Yet only a week ago, this smiling sea was possessed by howling winds and giant waves. Extraordinary changes in the weather, aren't there? Why do the changes occur? That sky today; how blue it is! But then, it always is blue on clear days. Did the gentleman know that the summit of the distant mountain pierced through the blue sky, that its own sky was almost black? He knew that the white was snow, that it meant freezing temperatures at the same altitude straight above the ship also. Did he know that stratosphere flights have shown a "reversing layer" far above the summit, where temperatures rise instead of fall with increasing altitude? But he wasn't going up, so what concern could that be to him? The mantle of snow and ice on the mountain; did he know, would he have cared to know, that it was destroying the mountain?

The afternoon lengthened, the sunshine was more tolerable, and the shadows were longer. But that always happens on bright summer afternoons, and there's nothing we can do about it. What concern of ours that the sun moves across the sky every day? Why worry about how hot the sun itself actually is, how much of its radiated heat the earth receives, why it is hot, how long before it will cool off and the earth's oceans then turn to solid rock? What a stupid planet to live on! Just land and water and air, and the sunshine over all!

Our friend's vocabulary doubtlessly contained the words "oxygen" and "moon" and "dust." Probably he could have offered them in response to some of these queries. That would be more than the clam-digging Indians on the beach a hundred years ago could have done, more than Jersey cows will ever

be able to do, however carefully they are bred for another thousand years. But the queries did not ask "what"; they asked "why." If "why" had never been asked in the history of the world, the bored gentleman would have been out on the tide flat with a sharp stick on this Sunday of ease and comfort, grubbing up clams to quiet the unpleasant grumblings of an empty stomach. During the three-day storm a week before the excursion, he would have been cowering under a shelter of bark, miserably cold and wet and nearly starved. His easy world of dominion over so much of nature (and this is your world, and mine) is the gift of men who could see things, who were downright curious about what they saw, who asked "why".

None of the questions we asked of the gentleman were

FIG. 1. "This little island now falling astern!"

"practical," none dealt directly with comfort in, or control over, physical surroundings. Curiosity alone prompted us. Only the fun of knowing and of understanding could be our immediate reward. Everybody enjoys outsmarting the clever author of a detective story, knowing before the denouement who did the murder in the Rue Morgue, what Sherlock Holmes saw in the tobacco ash. Almost everyone likes crossword puzzles. Some can see nature's questions and like to unravel them. Puzzles, of one kind or another, usually are fun. Here, even on this excursion steamer, innumerable problems stare at us. And if anyone yet knows the solutions, it's not because there was originally a book of answers.

For example, this little island now falling astern! (Fig. 1.) It has high cliffs facing the open ocean, none at all on the side

toward the bay. There are sand dunes on the top of the cliffs—a queer place for dunes! There is shallow water for half a mile out in front of the cliffs (see how those waves curl over into breakers!) and then a steep descent into deep water. Let's ask how much the island has been changed since it first was an island. Has it lost area, and the sea gained correspondingly, or vice versa? Have both coasts had the same history? How much has been gained by the winner? Is the change still going on? How rapidly, if at all? How long ago did it begin? All these questions can be answered, and without a book or a lecturer. Let's ask another question, prying still farther back into history. Where did the islands come from? They weren't towed in here from some other place. They didn't just grow, like mushrooms, or trees, or Topsy. Are they uplifts from the bottom of the water? Are they only remnants of a once continuous land, before there were any inlets to separate them? If so, how were the inlets dug? Where should we go for the answers? Would the shapes of the hills give a clue? Would the materials the waves are quarrying out, at the foot of the cliffs, be significant?

The clam-digging Indians who found their food on this beach a century ago were in the Stone Age.* Though their physical environment was the same as ours today, they never lifted themselves above primitive levels. They lacked something the advancing races have possessed. That something was "curiosity." Of a higher order than the curiosity of the Elephant's Child, though just as insatiable, it might be called a desire to understand things, or a love of truth or of knowledge, or the scientific attitude of mind, or the spirit of research. Do you remember about Benjamin Franklin's kite, the thunderstorm and the electric spark he got from a key? Have you heard the story of his retort to a challenging "What use is that?" He is said to have replied, Yankee-like, with another question: "What use is a new-born child?" Usefulness is generally a secondary consideration at the time of discovery. It may be

* Where our ancestors were 250 centuries ago.

trusted to appear in due time. Men who work on the puzzles of nature do it primarily for the fun of the thing. Michelson, when asked why he worked for years at measuring the velocity of light, always said, "Because it's good fun."

Our physical environment is fundamentally interesting. To know it is a pleasure, to understand it is a joy, to solve its puzzles is creative work of the highest type.

THE ENVIRONMENT'S LARGER ELEMENTS. Here we are, marooned on the earth. Though the astronomers, peering out into the illimitable oceans of space, may amaze us with what they find, there's no use thinking we'll ever escape. For a lifetime's sojourn, we shall have to get along with land and water and air, and each other. We are marooned on a floating island. It turns around once a day, and it moves along a path that closes on itself, is almost a circle. In the center of the circle is another floating island, a million earths in magnitude, hot beyond all terrestrial comparison. It bombards our little home island and all the other planet islands and all the vast emptiness among them with a never-ceasing barrage of radiant energy. We catch only one two-billionth of the outgo, yet if we stopped turning the hot side away to cool, and the cool side around to be warmed, there shortly would be no writer or readers of this book.

The earth is not a homogeneous unit; it is layered with the densest material on the inside, the lightest on the outside. Solid, liquid, gas; the earth is made of all three forms of matter and, where we live on it, all three come into contact with each other.

That contact of air and water and land, and that bombardment of radiant energy; there are no two more significant facts in this book.

The substance of the gaseous sphere (*atmosphere*) is mobile; is readily expanded and contracted by temperature changes. From the daily and yearly variations in exposure to the sun's radiation, it develops a circulation. Major currents like the trade winds sweep over large areas constantly throughout most

of the year. Minor ones come and go with the day and night or with the alternation of clear and rainy weather.

The liquid sphere (*hydrosphere,* oceans) is also mobile and is capable of a really extraordinary thing. Some of its substance may leave the liquid state to become gaseous, a part of the atmosphere, and later return to liquid again. Because the change is so common we seldom think of it as significant. This cycle of evaporation and condensation is conditioned likewise by rotation and revolution before the blazing central orb.

Circulation is the key word here. The energy of the sun runs the untamed winds, it lifts millions of tons of water from the oceans. As clouds or as a part of the atmosphere, much of this evaporated water migrates beyond oceanic limits and later comes down as rain on the lands. The descending rain, exceeding the pore capacity of the soil and rock, may stand in hollows as ponds and lakes. Most of it, however, flows down the land slopes, forms streams, returns to the oceans from which it came. As long as air and water have existed on the earth, this great cycle has been active. There's no beginning to which we can point, there's no running down in sight.

Air and water are not frictionless as they flow. They drag bottom. A part of their energy of motion is consumed in transporting loose bits of the solid part of the earth. The transportation is almost invariably down slope. Dust storms and drifting sand are present-day manifestations of work done by the wind; muddy rivers and shifting sand bars tell of similar work by streams. Though the work is generally inconspicuous, rarely spectacular, the aggregate results wrought in a single year by winds and streams are very great. Working throughout the centuries of the past, these circulations have enormously altered the face of the lands.

The task of the sun-driven flowings of air and water is the destruction of the land, the making of a universal sea. How they work toward this end, what assistance they receive, what opposition, how far they have gone toward their goal: these are

to be considered later and in more detail. Their work certainly is far from complete, obviously is going on today. We have settled on our island-in-space before it was quite finished and find it all the more interesting for that reason.

When the more violent manifestations get newspaper notice, it is chiefly because our lives or welfare or property are concerned. Great extremes in the weather always make news. Great storms on land or sea, great river floods: these may suddenly bring death and destruction. But, may it be repeated, most of this work of air and water is so slowly and so quietly performed and affects us so little in the span of a lifetime that it escapes general attention. But by no means is it therefore insignificant or uninteresting.

The rock sphere (*lithosphere*) is the external part of the solid earth. On it lie the hydrosphere and the atmosphere (Fig. 2). The rock sphere has an irregular surface and there isn't enough water to cover

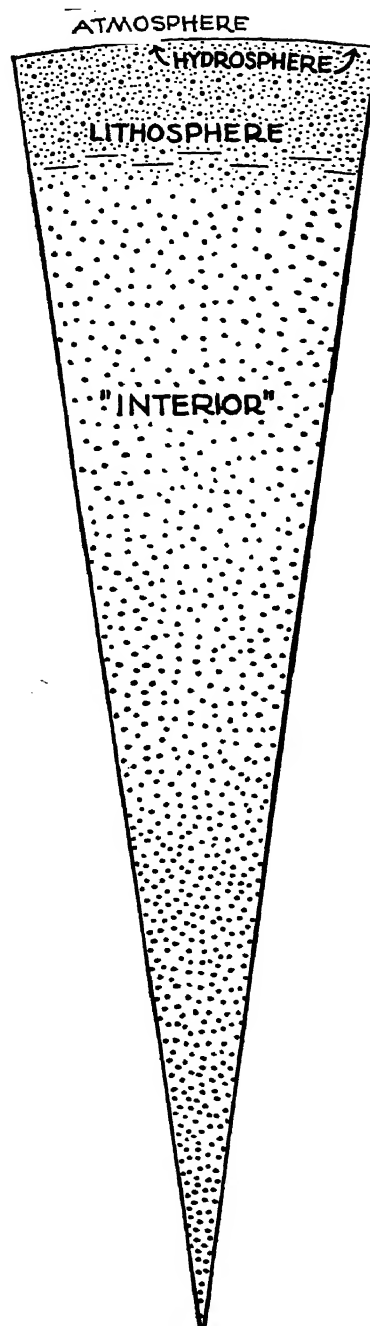


Fig. 2. A Section of the Earth's Three Spheres, Drawn to Correct Scales.

Upper limit of atmosphere assumed, not known. Thickness (depth) of hydrosphere correctly shown by width of line separating atmosphere and lithosphere.

it all. Higher portions projecting above sea level are the lands, largely aggregated into six continental units.* Thus the three layers, solid, liquid, and gas, occur over about three-fourths of the earth and only two layers, solid and gas, over the remaining fourth.

The liquid isn't all limited to the oceans, as everybody knows. Lakes and rivers occur on the land and almost everywhere there is water in the ground. With a little imagining, we can extend the water across the land to make the "hydro" a complete "sphere." The character and action of the earth's liquid water in the oceans is one thing; and on the lands, quite another.

Stream water is the most obvious and most important form of land water. But perhaps a third of all precipitation soaks into the ground and migrates downward as far as cracks and pores exist. Mines, wells, nearly all deep excavations encounter ground water. It is not commonly stagnant; there is generally a slow circulation. In some places, the flow is concentrated to resemble that of a surface stream. In some places, the ground water escapes to the surface as springs. Except in limestone caves, the work done by ground water is not conspicuous. Its changes seldom are topics of conversation or newspaper comment. But our ignorance of ground water and its work is of consequence only to ourselves. Nature's changes go serenely on, with or without our recognition. We now and then come to grief because we fail to know and to understand.

One of the minor Grecian personifications of the earth's water was Proteus, able to change his form at will. He should have been the major deity of the group. Water's protean nature includes the change to solid form under the low temperatures of high altitudes and high latitudes. Ice on the sea is not the same thing as ice on a lake. Ice on rivers does things neither lake nor sea ice do. Ice in frozen ground acts quite

* Is there a problem here? What if all the land occurred in equally spaced little islands of uniform size? Would that be "queer"? Only because land doesn't so occur! The commonplace, seldom interesting, is just as significant as the unusual or the queer. And there's a cause for everything, even the continental massing of lands.

differently from ice in any other situation. And ice from the packing down of deep polar and alpine snow makes glaciers, the most remarkable of all ice accumulations on the earth.

At the bottom of the hydrosphere's great reservoirs, the oceans, there is almost no destructive change. For there is almost no movement of water. The rule is reversed here, construction occurring instead. Consider the fate of dust blown out to sea from the land, of mud carried by rivers to the sea, of debris dropped from melting icebergs, of volcanic ash settling over the ocean, of the bones and shells of dead marine animals. All go to the bottom. As long as oceans have existed, they have been receiving waste material and accumulating it in layer upon layer on their floors. Most of this waste has come from the land, most of it has been loosened and transported downgrade to the continental margins by reason of that bombardment of solar energy and its activation of the two mobile films of air and water.

Yet the ocean provides important agents of degradation. Winds blowing over it produce traveling waves. Their energy of motion does nothing to the bottom in deep water; the wave disturbance is relatively shallow. But waves which encounter a shore are stopped by it. Their energy makes of them a powerful agent of attack on the land. Everybody knows how they may undercut a cliff, may destroy coastal land. The attacking waves, and currents engendered by their onslaught, give us one more manifestation of solar energy's intolerance of land, its constant efforts to make a universal ocean.

Tokens of an uncompleted earth are not limited to these sun-born activities in the mobile gas and liquid parts of the earth. The solid part has its own energies and its own changes. Your newspaper has something to tell about them every few weeks; sometimes they make the headlines. Who does not know that certain districts have far more earthquakes than the average; that, for most of the land, quakes of disastrous magnitude never occur; that there are regions repeatedly in the limelight because of volcanoes and their activity? Sunshine does not engender these things! An earth without air or water would

not thereby be immune from them. Clearly, energy sources exist within the body of the earth itself, and clearly the earth must be changing internally to produce these surface displays.

Since we live right in the contact zones of air and water and rock, we know what solar energy is doing to the earth much better than if we lived in a stratosphere balloon, miles above the contact. For the internal changes, we are far above the scene of action and our understanding is consequently more limited. However, we detect and measure the fainter pulses of the earth with seismographs, we make careful case-history studies of certain active volcanoes, and we are not altogether ignorant of the character of Pluto's underworld.

Though much of the content of this book is "geology," our knowledge of the earth has grown to such vast proportions and its different phases require such specialized training and technique that there are today no geologists in the older sense of the word. Specialists in volcanic phenomena cannot well know more than the general facts and theories of the rest of earth phenomena. They are volcanologists. Specialists in the subject of earthquakes and their causes are loaded to the human limit in encompassing their own field. They are seismologists, another species of the genus geologist. Similarly, there are stratigraphers, physiographers, glacialists, paleontologists, sedimentologists, mineralogists, petrologists, and many others, all geologists in the broader sense, students of some special part of the enormous field of earth knowledge (*Ge*, Greek for earth). Closely allied are the oceanographers and the meteorologists, one obviously dealing with the oceans, the other, not so obviously,* with the atmosphere. The men of the weather bureau are meteorologists.

Remembering the intimate way in which the changes in air and water and rock are interrelated, one sees why there

* The dictionaries define *meteor* as (1) any atmospheric phenomenon, (2) a shooting star, the fallen body being a meteorite, and (3) a body moving in space beyond our atmosphere, of the same nature as a shooting star. The word *meteorology* comes from the first definition. It is the science of all atmospheric phenomena.

can be no high board fence about any of these subjects. Nature has infinite gradations and interrelations. In pursuing one subject, we are likely to find ourselves crossing our artificial line into another. That's not trespassing. The men across the line can help us with their fuller knowledge of the entered field and we can contribute something about our province to help them better to understand their own. Despite increasing subdivision within the larger field, overlaps hold the subdivisions together. Large overlaps are seen in geology's need for physics and chemistry. So in paleontology, the knowledge of fossil animals and plants, there is a large overlap of geology and biology. The earth sciences all weld together into one coherent whole when we see them as interpreters of our terrestrial environment.

BIBLIOGRAPHY

(The books regarded as most essential are marked with an asterisk.)

Agar, W. M., Flint, R. F., and Longwell, C. R., *Geology from Original Sources,* Henry Holt and Company, New York, 1929.

Excerpts from more than a hundred classic studies in geology. A library in itself.

Allen, V. T., *This Earth of Ours,* Bruce Publishing Company, Milwaukee, 1939.

Well-written, splendidly illustrated. About a third of it deals with earth history and the development of living forms.

Croneis, C., and Krumbein, W. C., *Down to Earth,* University of Chicago Press, 1936.

A big book but written for college students. Rotogravure and comic line illustrations. Not everybody likes this book, but those who do think it is great. About half the book is devoted to earth history.

* Finch, V. C., and Trewartha, G. T., *Elements of Geography,* Chapter 14, McGraw-Hill Book Company, Inc., New York, 1936.

Hobbs, W. H., *Earth Features and Their Meaning,* The Macmillan Company, New York, 1931.

A 500-page book containing the material of a half-year course given by Professor Hobbs at the University of Michigan. Purpose is the interpretation, and therefore the intelligent appreciation, of landscapes.

Lobeck, A. K., *Geomorphology,* McGraw-Hill Book Company, Inc., New York, 1939.

More than 700 pages on land forms and their origin. Two-thirds of the book consists of splendid photographs, maps, and diagrams. "The most beautifully illustrated text in all geological literature."

LOOMIS, F. B., *Physiography of the United States,* Doubleday, Doran and Company, Garden City, 1937.

A quarter of the book covers the field we have described here as "The Solid Earth." More than 200 pages on the nature and origin of the twenty different physiographic provinces of the country.

CHAPTER II

THE EARTH'S GASEOUS FILM

THE SKY. The "sky" is a creation of our atmosphere. Its varying illuminations and colorings are modifications of impinging sunlight by the air the light passes through. The blue sky is limited to the lower few miles of the atmosphere because here is most of the dust and moisture and the greatest density of air. Observers on high mountain summits and high balloon flights report a black sky above a blue horizon. The blue is mostly below them. At the bottom of the atmosphere, where most of us must always stay, the blue sky grades into grayish or whitish nearer the horizon. The sun's color, yellow from ground level, is white at very high altitudes. All these variations are effects of the air on the many-colored "white" light of the sun. So the marvelous sky colors of sunrise and sunset * are due to breaking up of the sun's white light as it then reaches us horizontally through many more miles of dense, dust-and-moisture-laden air near the ground.

COMPOSITION OF AIR. Is air a simple homogeneous substance? More than two thousand years ago, Aristotle said, in effect, "No, it contains at least two substances, water vapor and something else." What the "something else" was, whether it was a simple substance or a mixture of several substances, these questions had to wait more than two millennia for answers; and they never would have been answered if the science of chemistry had not developed. Quaint notions came and went in the early days of chemistry. There was the idea that a substance called phlogiston escaped into the air from any burn-

* If a colored sunset occurred only once in ten years, you wouldn't object to that word "marvelous."

ing substance. Ashes and rocks couldn't burn, for they contained no phlogiston. The terms "fixed air," "dephlogisticated air," "mephitic air," were applied in various early attempts to analyze the "something else" of Aristotle into separate components. We may smile at all this, for we say carbon dioxide instead of fixed air, nitrogen instead of mephitic air, oxygen instead of dephlogisticated air; we never mention phlogiston, we know so much more than the first investigators did. But our smiling is hardly fair, for this pioneer work was absolutely essential to the growth of today's knowledge.

The "something else" of Aristotle is 78.03 per cent nitrogen, 20.99 per cent oxygen, .93 per cent argon, .03 per cent carbon dioxide; and the remaining small fraction of 1 per cent is composed of five more elements. Here we shall consider only the analysis of Aristotle. The air is composed of water vapor and "something else," which we shall call dry air. This simplicity won't do, however, when the interrelations of air and water and of air and rock come up for attention. Oxygen is very active chemically, ties up with anything not fully oxidized. Nitrogen is just inert bulk. So is argon. The exceedingly small percentage of carbon dioxide plays vital roles, of which most people are as serenely unconscious as they are of its existence.

Conceive of a planet like ours in every respect except that its air contains no oxygen. Or that the relative proportions of nitrogen and oxygen are reversed. Or that carbon dioxide amounts to a round one per cent. Any one of those changes would make that planet very different from the one we live on. Perhaps memory will recall this statement when you have read all this book; perhaps you will then list some of the differences you will have discovered. A complete list would require collaboration of a biologist, a physicist, a chemist, a physiologist, a meteorologist, and a geologist.

DENSITY OF AIR. Gas is highly compressible, in contrast with liquid and solid. The pull of gravity on the atmosphere compresses it. The bottom air, carrying the weight of all

the air above, is most compressed. Because one's body is adjusted to this compression, there is no discomfort, scarcely any consciousness of it. But try running at high altitude and note the difficulties heart and lungs and muscles encounter. There isn't enough air in a lungful to maintain exertions one easily performs at sea level. Mt. Everest, repeatedly attacked by the best mountain climbers in the world, is still unconquered. Its chief defense is the low density of air into which it soars. Stratosphere balloons have risen twice as high as Everest, their aeronauts hermetically sealed in a metal gondola. Outside temperatures at thirteen miles above the sea (80° below zero) were not impossible for human beings to survive for a short time, but, even if it were above freezing, no breathing organisms could live in that rarefied air.

No balloon ever has risen, or ever will rise, a quarter of the way (25/100) to the upper limit of the atmosphere; yet the Explorer II, in 1935, rose through 96/100 of the mass of the air over South Dakota.* At sea level, the air pressure or air weight is nearly fifteen pounds to the square inch; at the Explorer II's ceiling (72,395 feet above the sea) it was only six-tenths of a pound.

The radius of the earth is nearly four thousand miles. Ninety-five per cent of the air is within thirteen miles of sea level. This relatively extreme thinness of the gas layer justifies the term "film."

HEATING OF THE ATMOSPHERE. The distance from the earth to the sun is more than ten thousand times the diameter of the earth. The sun's rays, therefore, are essentially parallel on reaching us. If under these conditions the earth had a flat surface squarely facing the sun, the sun would appear exactly overhead everywhere (at noon) and every square mile would get the same amount of radiated energy. We know that this does not occur, that the position of the noon sun in the sky on any given day varies from place to place along a north-south

* Both statements are correct. Mass is commonly expressed in units of weight.

direction, that only one place (or places on only one east-west line) on that day has the sun exactly overhead (90° above the horizon) at noon (Fig. 3). This is good evidence that the earth's surface is curved. And since the height above the horizon of the noon-day sun becomes almost uniformly less with increasing distance north or south of that east-west line, we believe the earth's surface is nearly spherical. Add sunrise, sunset, and midnight to complete the concept; this sphere turns around once every twenty-four hours.

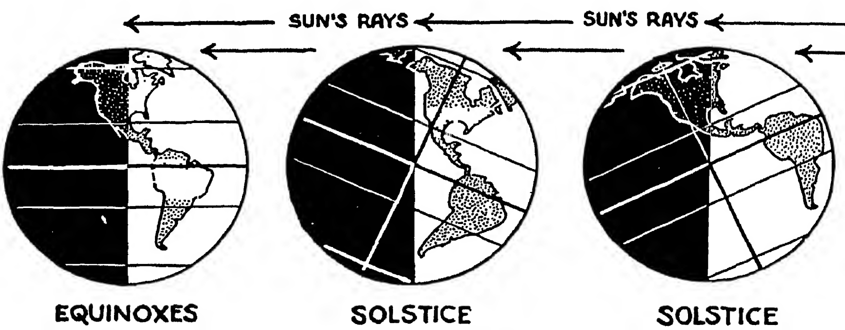


Fig. 3. It is noon (sun time) at all points on that edge of each diagram toward the sun, and midnight on the opposite edge. It is 6:00 o'clock (morning? evening?) everywhere along the line separating the lighted half from the dark half. What time of the year—month, day, *season* (be careful)—is shown in the third diagram? How many hours of daylight does the area within the Arctic Circle have for the day shown in the middle diagram? Shouldn't there be a fourth diagram? The earth's axis always points in the *same direction* in space, yet the diagrams are correct! What's your explanation? (After Ridgley and Koeppe, *A College Workbook in Weather and Climate,* McKnight and McKnight, Bloomington, 1930.)

Thickness or depth of the air is the same in all latitudes. Compression of the lower air from the weight of that above must therefore be the same. Yet sea-level pressure is not the same all over the world. There must be another controlling factor determining atmospheric pressure. That factor is the great variation in sea-level temperatures. Air runs a temperature only because the sun shines on it. The relatively dense lower air, containing dust and lying on warm land surfaces, becomes most warmed. The greatest *insolation* (heat received from the sun), and consequently the greatest heating of the

lower air, occurs in equatorial latitudes, the least occurs in polar latitudes (Fig. 4).

CIRCULATION FROM DIFFERENCES IN HEATING. Air expands when heated. Any cubic unit (foot, mile) contains less air after expansion; hence weighs less; hence at sea level below it there is less pressure. These differences in pressure are not perceptible to our senses but are enough to produce

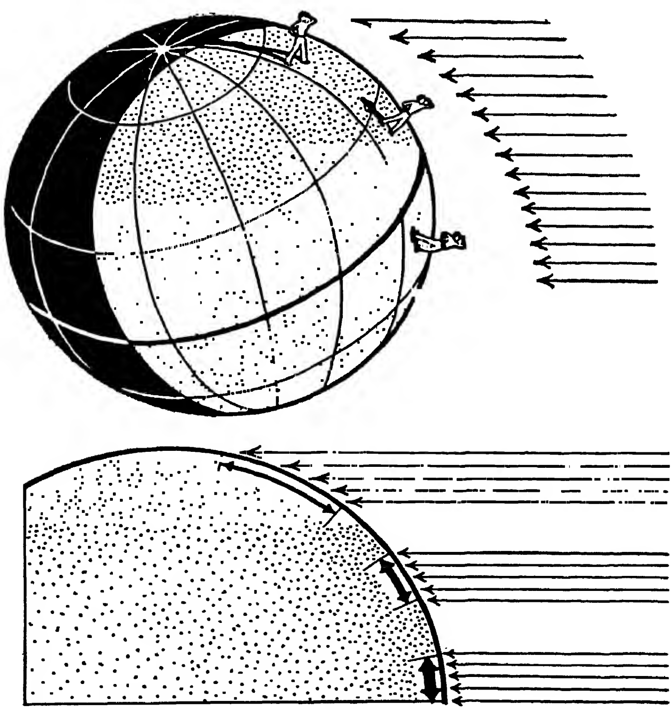


FIG. 4. Insolation in Different Latitudes.

very important results in the atmosphere. If at sea level (or any other level, for that matter) adjacent areas differ in their air pressure, there obviously will be a flow from the tract of higher pressure to that of lower. This is wind, air in horizontal movement. Windless air is air in equilibrium, i.e., under the same pressure everywhere in any given level. The greater the difference in pressure at any one level, the stronger the flow. The more constant the difference, the more constant the flow.

The fewer and weaker the interfering factors, the more direct the route of flow.

Stratosphere and troposphere. Unsuspected only a few decades ago was the existence of a *stratosphere* portion of the atmosphere, sharply marked off from the lower air at heights grading from six miles above the sea in very high latitudes to ten miles above in the tropics (Fig. 5). The stratosphere air is cloudless and almost wholly without water vapor, while the *troposphere,* between it and the ground, carries all the clouds, yields all the rain and snow. The stratosphere air is almost uniform in temperature as far up as sounding balloons have gone (twenty miles), and perhaps actually increases a little in temperature with increasing height. The troposphere part, in contrast, has a notable thermal stratification, warmest at the bottom and below freezing even in summer at altitudes of a few thousand feet. The stratosphere is almost without turbulence, whereas the troposphere is almost everywhere disturbed by vertically rising and descending air currents. "Bumps" of the aviator's experience are rising currents, "pockets" or "holes" are descending ones. The stratosphere air is almost perfectly dust-free; all troposphere air contains dust.*

Planetary circulation. We are talking now about what are called the planetary winds. They affect large areas of the earth; they blow (with some shifting and some interruptions) throughout the year, they are due to this difference in pressure from difference in heating in high and low latitudes. If the earth did not rotate and did possess a universal ocean, the planetary circulation would probably consist of

* The intensely cold, dry, low-pressure stratosphere is only a few miles above us, and the intensely hot, high-pressure interior of the earth only a few miles below. How extraordinarily "thin" is the zone in which life can exist on the earth! But before this book is outmoded, those high stratosphere levels will be invaded by aeroplanes whose sealed cabins will contain their own "atmospheres," with temperatures and pressures suitable for human comfort. Above all clouds and storms, above all mountain peaks, above the greater air resistance of the troposphere will be the fastest express routes ever to be attained.

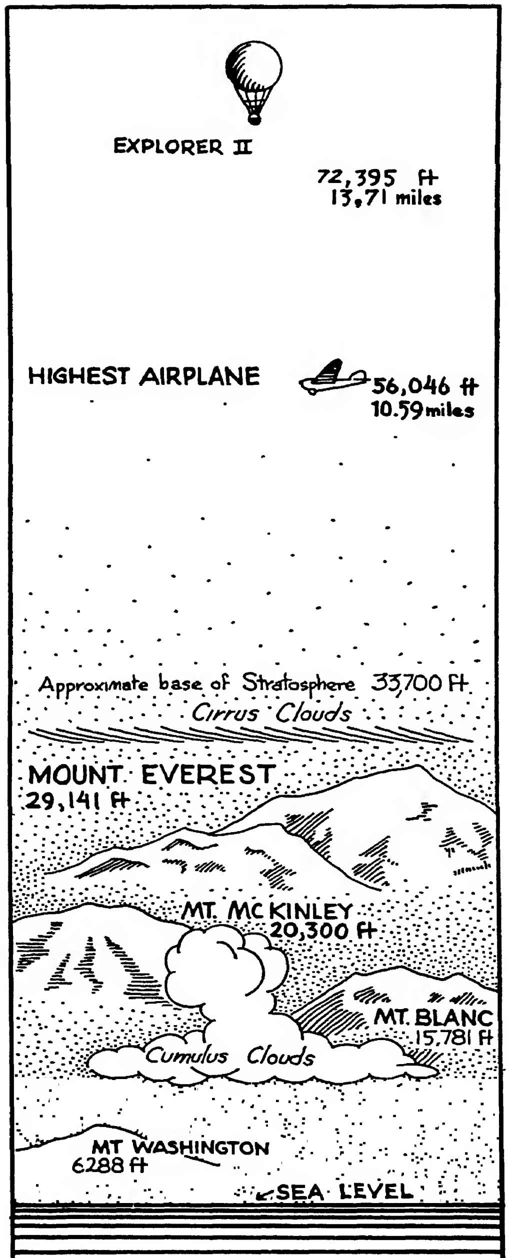


FIG. 5. Troposphere and Stratosphere. (After National Geographic Stratosphere Series No. 2, page 208.)

cooled (contracted) air settling down on the two polar areas, flowing over the sunlit surface toward the equatorial region, becoming most warmed (expanded) in the tropical belt, there rising to flow back poleward within some six to ten miles of sea level (below the bottom of the stratosphere), cooling, settling again, beginning again the great cycle.

But because the earth rotates, the actual winds are deflected from the theoretical north-south courses. And because large land masses alternate with large water areas underneath the air, heating (and therefore pressure) of the bottom air varies in the same latitude. So the planetary wind system is far more complex than it would be on a non-rotating earth with no lands interrupting the continuity of the oceans.

The particular winds of the planetary system which affect our latitudes are the prevailing westerlies, blowing from the southwest across the United States and southern Canada, bringing our Gulf storms, dust storms, tornadoes, heat waves. Though they originate in southern United States and northern Mexico, the air of which they consist comes largely from the equator. Over equatorial latitudes lies a great belt of heated air, the warmest part of the entire atmosphere. Its pressure is low because its temperature is high. Cooler air flows in at the bottom from both north and south. In the belt the air is rising, and, since vertical movement is not wind, it is reckoned as a belt of calms, the *doldrums.* That warmed air, after rising, spreads out at an altitude of two or three miles, part flowing southward, part northward. Removed from the place of heating (contact with land and water) and now somewhat cooled by expansion,* it settles slowly as it flows and, at latitude about 30° north and south of the equator, much of it descends to the ground again. This also makes a belt of calms, the *horse latitudes,* one in each hemisphere just outside the limits of the tropical zone. In contrast with the doldrums over the equator, air in the horse latitudes is descending. So, on the surface, air flows away both northward and southward from

* Have you ever removed the valve core of a hot tire and discovered that the escaping air was cold?

the horse latitude belt of calms (Fig. 6). That which flows poleward becomes the *prevailing westerlies* of each hemisphere, that which flows equatorward becomes the *trade winds*. The westerlies, reaching higher latitudes, are frequently interrupted by wedge-like masses of cold polar air thrusting under them and

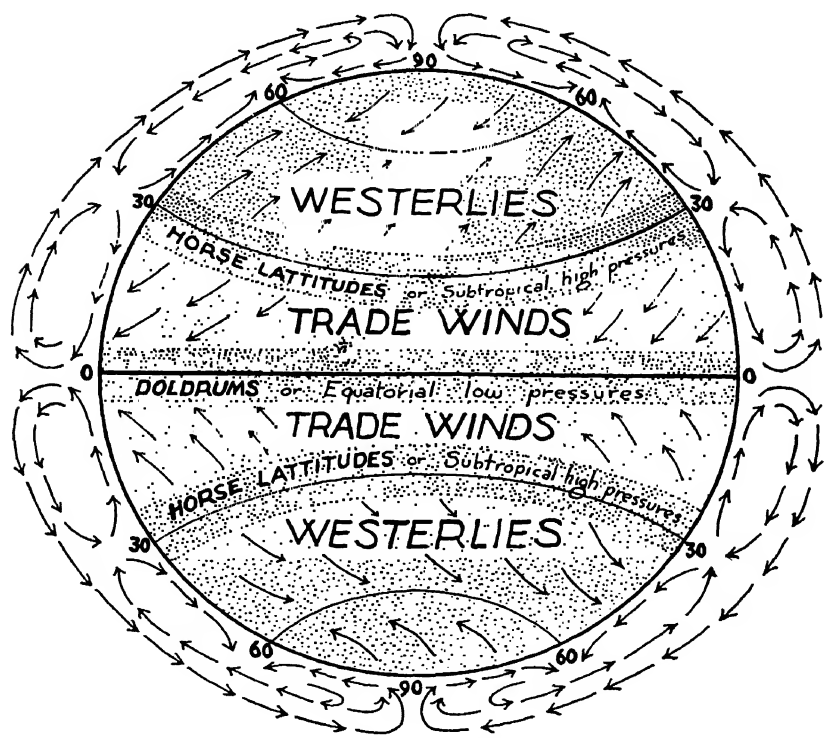


FIG. 6. The Planetary Circulation. (After Ridgley and Koeppe, *A College Workbook in Weather and Climate*, McKnight and McKnight, Bloomington, 1930.)

escaping to lower latitudes (Fig. 7). These produce the cold waves of winter and the cool, clear spells of summer.

ROTATIONAL DEFLECTION. Rotation of the earth, from west to east, imposes on every wind of the planetary system a deflection from a north-south course. Consider the trade winds. They supply the great equatorial belt of rising air. Indeed, they actually push it up, for their air is cooler, denser, heavier. Instead of flowing directly to the equator, however,

they flow diagonally westward toward it, falling constantly behind with reference to the east-traveling land and water beneath as they flow. Consider also the *anti-trades* and their continuation in the prevailing westerlies. As they flow away from the equator their course becames more and more easterly * until it is perhaps more east than north or south. They are getting ahead of the longitude in which they started. Why should their deflection be to the east when that of the trades is to the west?

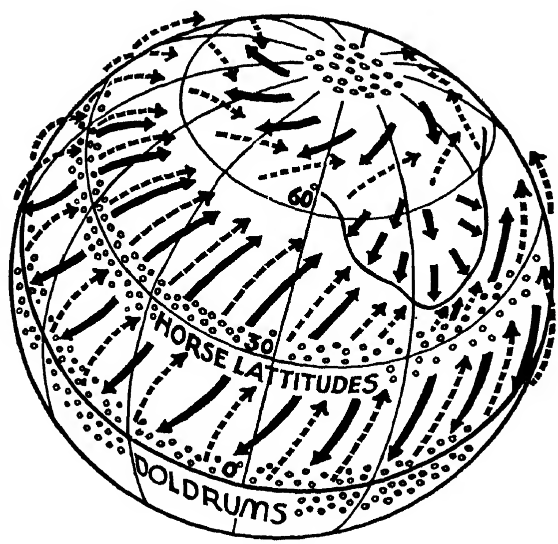


FIG. 7. Interruptions in the Westerlies.

Diagram shows a wedge of sub-arctic cold air temporarily displacing a part of the westerlies. Surface winds shown by full-line arrows, upper winds by dash-line arrows.

Both deflections result from the wind changing its latitude. Think of a mass of windless air standing over the equator. But it isn't standing; it is riding along with the rest of the rotating earth. Twenty-five thousand miles, the length of the equator. Twenty-four hours, the round trip. Think of this mass of air becoming warmed and rising. If it stays over the same region, it is still traveling eastward about a thousand miles an hour.

* Isn't that why so few of the early aeroplane flights across the Atlantic were made from Europe to America?

But it now flows away from the equator to higher latitudes in one of the two anti-trade winds. Latitude lines become shorter as the equator is left behind. There are fewer miles to be traveled in the twenty-four-hour rotation trip. So the poleward-flowing air constantly moves to regions whose speed of rotation (in miles per hour) is less than that of the region which it has left and whose speed of rotation it once possessed. Something like stepping off a moving car, isn't it? Except that you shortly come to a dead stop, whereas the air continues to move on. Momentum throws the air forward, eastward, out of its direct poleward route. Conversely, the trade winds, moving toward the equator, are left somewhat behind, and arrive at the doldrums far west of the longitude from which they started.

This, briefly, is the general circulation of the atmosphere (Fig. 8). Though far more is known about it than is here presented, meteorologists bemoan the scantiness of their data and endeavor by sounding balloons (with recording instruments), and by stratosphere balloons and aeroplanes (carrying observers with instruments) to explore the atmosphere more adequately, to learn of winds in its higher parts, of its pressure variations, of its temperatures, of its varying humidity.

The planetary wind system is an earth-big, warm-air heating plant, heated from above in low latitudes, cooling above in high latitudes, and the cooling as necessary to its functioning as the heating. Its circulation is thermodynamic. Superposed on it, or included within it, are many smaller circulations. These smaller features, like the general system, are largely dependent on differences in temperature (and therefore pressure) in horizontal directions.

DIFFERENTIAL HEATING OVER LAND AND WATER. Summer resorts not in the mountains seek higher latitudes, winter resorts seek lower. That's all in the angle of the sun's rays, for, whatever the season, the rays come down more steeply (through less air) in low latitudes than in high. But summer resorts not in the mountains also are almost invariably on lake or ocean coasts. Most winter resorts are on or

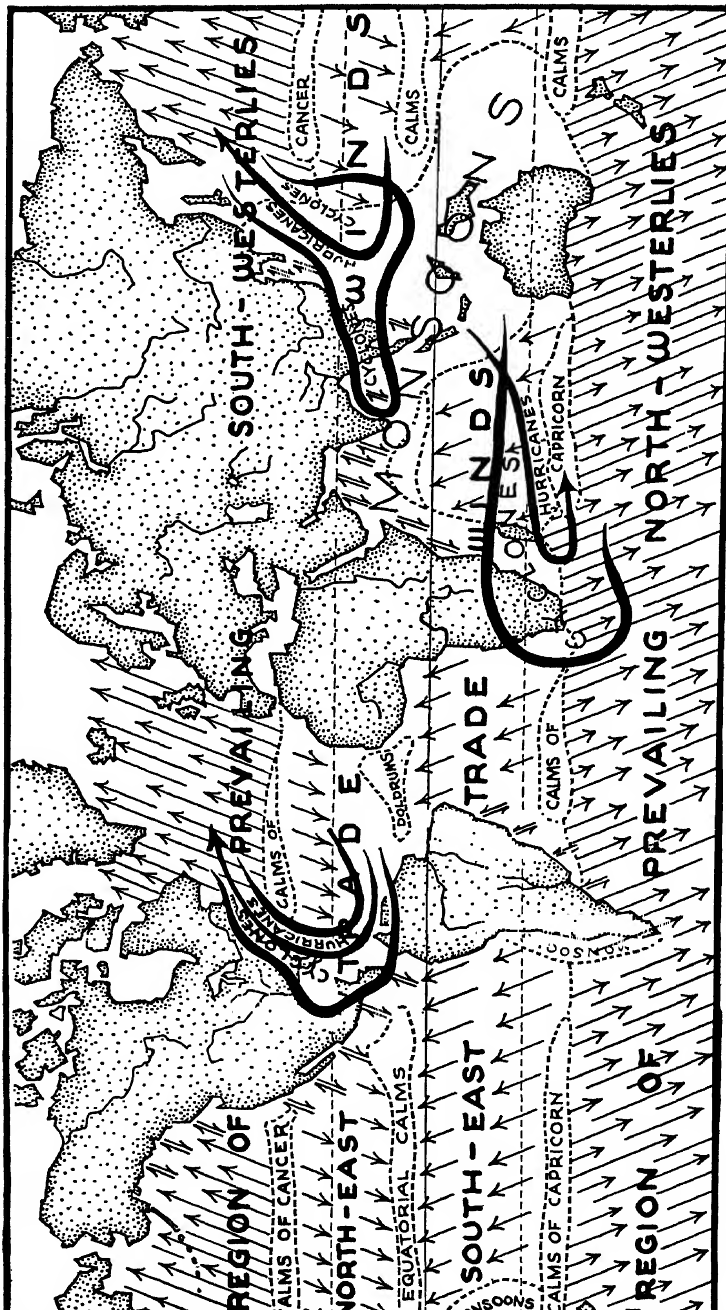


FIG. 8. Chart of the Oceanic Winds.

(After Hopkins, *Elements of Physical Geography*, Sanborn, Boston, 1908.)

Planetary Winds Monsoons

near coasts. Is there something about bodies of water which reduces the unpleasant extremes of each season?

Think of a large lowland area and a large water area, side by side in the same latitude. Each receives the same amount of insolation per square mile, has the same thickness of air above it, is affected by the same planetary wind. But summer on the land is hotter, and winter is colder, than on the water. The difference must result from something which happens to the sun's radiation after it has penetrated through the atmosphere.

Water reflects more radiation than does land. Stated conversely, the greater absorption of radiant energy by soil and rock makes them warmer than water in the summer.

Water may be called transparent, rock and soil are opaque. Radiation's effect will be concentrated on the very surface of the land, while it will be distributed through a considerable thickness of water.

Water circulates. Land material remains fixed in position; it cannot escape the bombardment of solar rays, and temperature must go higher so long as the bombarding continues unabated.

Water evaporates. Energy is required from the solar radiation to bring about and maintain this gaseous condition. Thus evaporation keeps the temperature of water lower than that of land.

Water has a "specific heat" four times that of rock. That is, four times as much heat is required to raise the temperature of a given quantity of water a specified amount than for the same quantity of rock. With equal insolation, land therefore gets warmer than water.

For these reasons the air over the land is warmer in the daytime and in the summertime than over water. But when night or winter comes, it is the land which cools more rapidly, and its air shares in the cooling.

Sea breezes. Your author lives in Chicago on the shore of Lake Michigan. It is the windward shore, as the prevailing westerlies blow, and a summer day in Chicago may be

very hot. Most of the city's refugees from summer torridity are in Michigan on the eastern, the leeward, shore. Those unable to escape the city pray for the lake breeze, a draft of cool air in the afternoon that may sweep over the entire metropolitan area, though its effect commonly extends only a few miles inland. The lake breeze is the same thing as the sea breeze, a summer afternoon alleviation familiar to many. The more heated air, lying over the land, develops a slightly lower pressure, is underthrust by cooler, heavier air from the lake or the ocean (Fig. 9). Calm weather is essential for the water-to-land breeze; almost any contrary wind may prevent its appear-

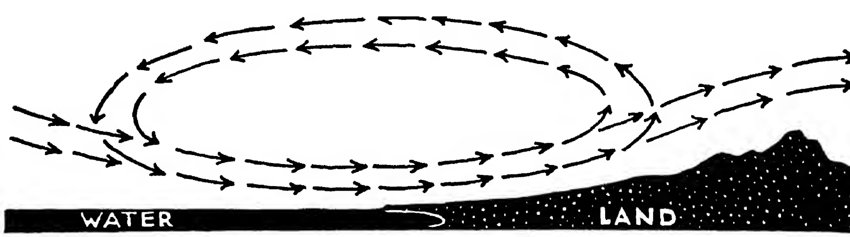


FIG. 9. Circulation of the Sea Breeze.
(Redrawn, by permission of the publishers, The Arthur H. Clark Co., from Lt. Harold L. Kirby's *Analysis of Meteorology as Related to the Operation of Aircraft.*)

ance. There may also be a weak breeze from land to water about dawn, if the land cools enough during the night.

MONSOONS. Of similar character and origin is another reversing land-water wind, the monsoon. It is seasonal instead of daily, blowing to the land in summer, to the sea in winter. Probably the best-known example of the monsoon blows from the Indian Ocean in summer, completely across India and up over the great Himalayan mountain wall, the highest wall on earth. It actually overcomes the trade wind, in whose belt it occurs. The winter monsoon, when the land is cooler than the water, blows out to sea, coinciding with the trades at that time.

RAINFALL. Everybody knows that some regions receive an excessive rainfall while others are woefully deficient in rain, and that in different places there are great differences

in the rain schedule. Some regions have two rainy seasons a year, some but one. In some, the summer is rainy and the winter dry; in others the reverse is true. In some, the rain occurs only in rare torrential showers; in others, it is a constant drizzle during the proper season. The general principles which determine rainfall and its variations are fairly simple, but the detailed explanation for any particular area's rainfall commonly is rather complex.

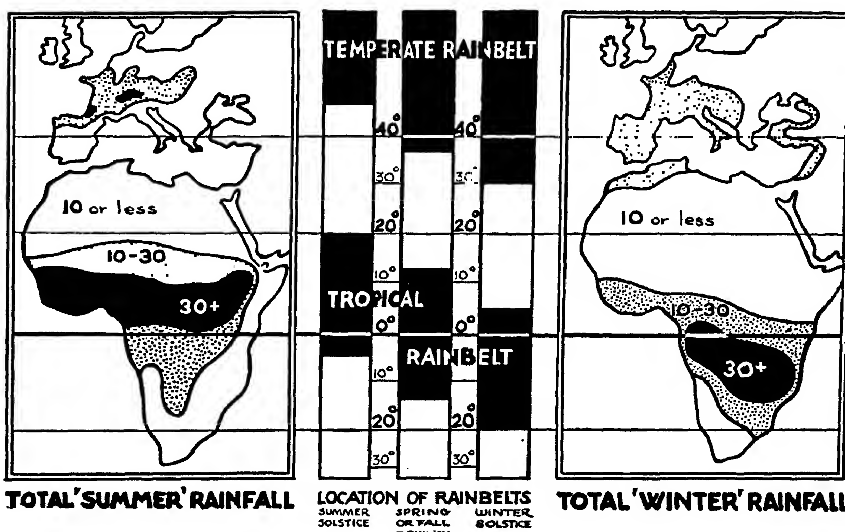


FIG. 10. Africa's "Summer" and "Winter" Rainfall. (Adapted from Herbertson) What justifies the quotation marks on the season names? Which summer (northern hemisphere or southern hemisphere) is shown at left?

A great rain belt surrounds the earth in equatorial latitudes. On land, it is marked by jungle regions in South America, Africa, India, and the East Indies. It is a shifting belt, migrating with summer.* It stands a few degrees north of the equator in July and August, then travels slowly back for six months to stand a corresponding distance south of the equator in January and February. Thus equatorial latitudes get two rainy seasons a year, and two dry ones.

The rain of equatorial regions comes in afternoon showers,

* Of course summer migrates.

when the air heated during the day rises in strong convection currents, and, lifted aloft, expands and its temperature lowers so much that heavy condensation of its water vapor occurs. Rising currents of course are characteristic, for this is the doldrums belt.

On each side of the equatorial rainy belt there is a belt of little rainfall, even desert country. The trades, sweeping ever nearer the equator, become progressively warmer (greater capacity for water vapor), become drying winds, bring no rain on sea or lowland. Likewise in the two horse latitude belts of calm, the descending air is becoming warmer, making for little rainfall.

Try to find this latitude pattern on the rainfall map (Fig. 11). It's difficult to see much more than a suggestion of it or any latitude control. Were there a universal ocean, the theoretical pattern might be realized, though the existing ratio of one of land to three of water isn't the whole reason for that very irregular pattern. A uniform spotting of nearly fifty-four million little islands * in an ocean of one hundred and forty-three million square miles probably would yield a definite latitude pattern. The existence of the great land lumps, the continents, determines much of the irregularity of the map. Then, because the continents are not pancakes but have mountains and plateaus rising halfway or more to the top of the troposphere, the irregularities are still more accentuated.

The heaviest rainfalls of the globe are locally determined by high lands in the path of prevailing winds. Even habitually rainless winds like the trades or the monsoons, when forced to rise over a high mountain range, bring heavy rain to the slopes they climb. "A garden, a wall, a desert" tells the story in one phrase. Arid deserts are just as logical in the lee of a mountain range as they are beneath the horse latitude calms. The same principle obtains. In each case, moisture had previously been squeezed † out of the air and afterward warming had increased

* How little? There are fifty-four million square miles of land on the globe.

† That's figurative, surely.

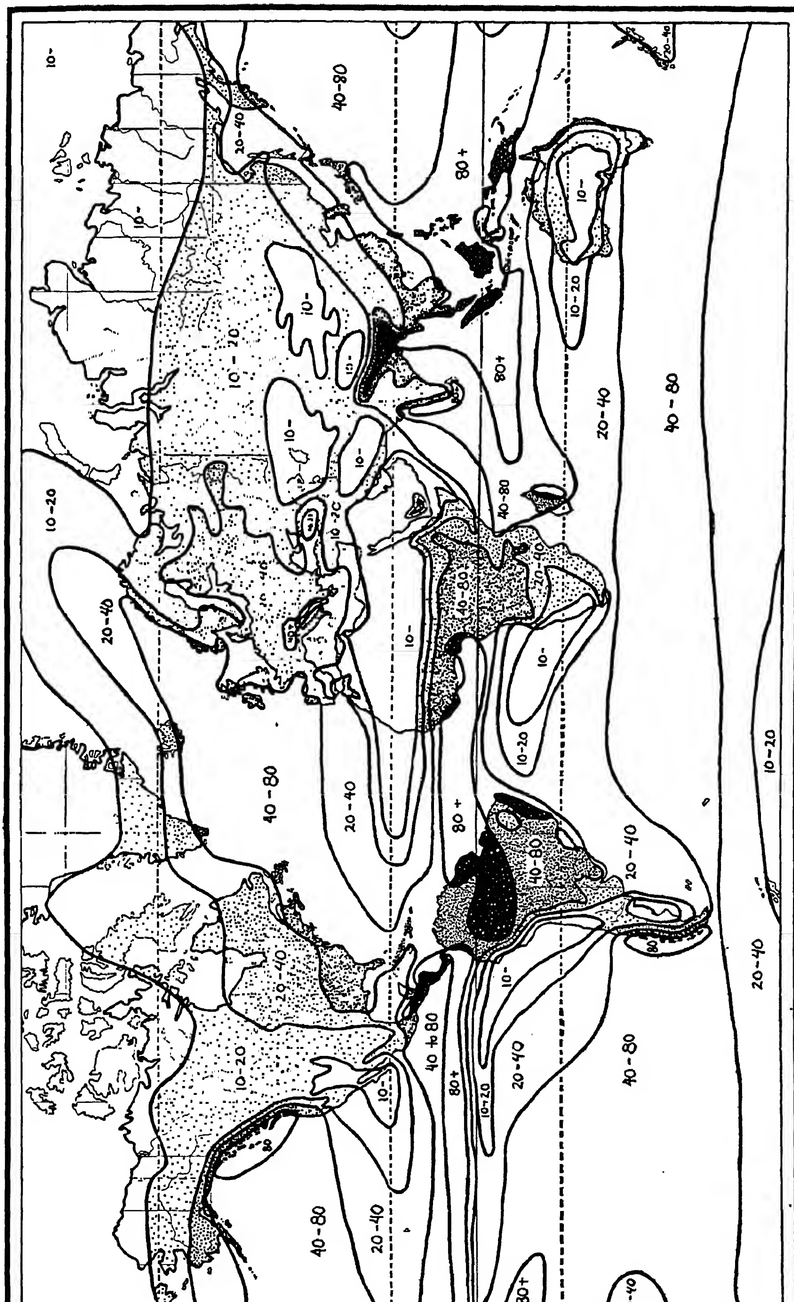


FIG. 11. Rainfall Map of the World. (After Schott, Supan, Hahn and Suring)

its capacity, had made of it a drying wind. Squeezing by cooling, of course, and cooling by rising. Then warming by descending.

Now the map again. Why the heavy rainfall of western Oregon, Washington, British Columbia, and Alaska? Find the location of the Himalayas! Which way do the prevailing winds blow on the Scandinavian peninsula? Why is western Peru arid and western Chile rainy, when through both runs the north-south Andean range? There are many rainfall problems in even this generalized map. Our rapid survey and quick arrival at conclusions must not give us the erroneous impression that the subject is simple.

Water vapor is the really variable constituent of the atmosphere and all because it is so sensitive to temperature changes. It is also the most important constituent so far as climate and weather are concerned. Just suppose our earth consisted only of lithosphere and "dry" atmosphere. No life, of course, but what else would be vastly different on its surface? Would there be planetary winds? Seasons? Would there be the same temperatures as now in the tropics and in the polar areas? If not, would the average temperature of each be higher, or lower? Would there be a greater difference than now (or less) between average tropical and average polar temperatures? A principle to be brought out in the next few pages will help to answer some of these queries.

WEATHER. Summer is the warm season of the year. It should be warm, of course, for then sunshine is reaching us at high angles through the atmosphere and we have more hours of daylight than of darkness. Winter, conversely, should be cold. But angle of the sun's rays and hours of daylight are astronomically fixed for any time of the year. Why, then, should some one winter carry off the prize for the coldest (or the warmest) in Weather Bureau history? Why should some spring have been the dryest, or some summer the wettest, or some particular month the cloudiest on record? Why should a today at 90° in the shade have a tomorrow cool enough for top

coats? And why should Chicago be deluged with rain when New York's sky is clear?

Mark Twain's gibe that "though everybody talks about the weather, nobody does anything about it" is not quite true. What if we don't control it? We forecast it, and accurately enough to avoid some of the penalties ignorance could bring.

The least observant person in the country knows that, though weather is proverbially capricious, there is a general rule for its changes in any season. A few clear days usually alternate with a few cloudy days. The average temperature of the clear days generally is lower than that of the cloudy days, though a sunny noon may be warmer than a cloudy one. Wind is more marked on the cloudy days; snow or rain comes then. Storminess is a relative term, but almost everything we call a storm comes on the cloudy days.

Weather observations beyond the ordinary recognition of "fair" and "foul" involve detailed measurements and records. Temperature, for example. Not how hot it was at 2:00 P.M., or how cold at 6:00 A.M., but what the temperature was at every hour of the entire day, of every entire day in the year. Precipitation, for another example. Not that it rained cats and dogs this forenoon, but how many inches, or fractions of an inch, of rain have fallen each day of the year. Air pressure, for another. Your senses were unaware of any pressure changes as the cloudy weather cleared up. But the meteorologist was watching a barometer or had a barograph in operation (*baro,* Greek for weight). During the cloudy weather the air pressure went down, and when the sky cleared for a few days it went up. Not spectacularly, of course. So many significant things fail to be spectacular! The pressure may have varied as much as an inch on the barometer, equivalent to changing our altitude about a thousand feet, while we remained at precisely the same altitude through it all.

WEATHER FORECASTING. An observer might measure and record at his station all his life, yet never be able to forecast much better than you or I. He could only guess from past

experience what was coming next. Suppose, however, that there were observers in several other places, a hundred miles or so apart, and that they all were in communication. That's precisely the way weather forecasting began. Benjamin Franklin first discovered what is commonplace knowledge today; that our weather generally comes to us from the westward and, on leaving us, affects regions progressively farther east until it goes out to sea. Most of our weather travels in the prevailing westerlies. Forecasting in our latitudes involves a knowledge of weather habits, and of existing weather west of the forecaster's station.

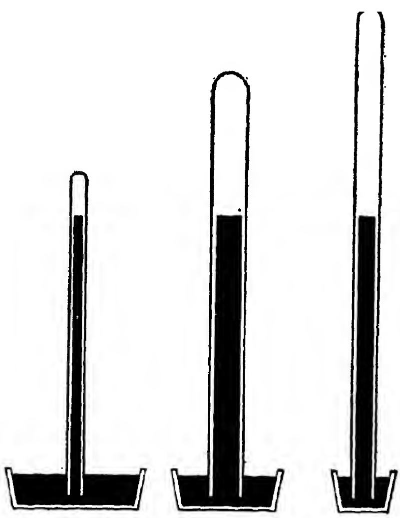


FIG. 12. Mercurial Barometers.

Whatever the diameter of tube, or area of cup, and whatever the length of tube (above 30 inches), the column stands at the same height.

The most significant item with which the weather man deals is the least obvious: the variations in air pressure. From it can be traced, as consequences, all the weather phenomena we so like to talk about. Navigators of the ocean and the air know this well, and intelligent voyagers journeying with them soon learn. Readers of sea stories have it dinned into them that "the glass is falling rapidly and there'll be dirty weather tonight."

The "glass" is a tube more than thirty inches long, closed at one end, filled with mercury, then inverted with its open end below the surface of a pool of mercury in a cup. You've probably done the same thing in principle with a drinking glass upside down in a dish pan full of water. Air pressure on the open water surface keeps the glass filled. Suppose the glass were so long that when inverted its contained water weighed more than a vertical column of air of the same diameter from the water surface to the top of the atmosphere (it would have

to be more than thirty-three feet long) (compare with Fig. 12). Then the water in the top of the now inverted long tube would lower until its weight was just balanced by the weight of an air column of that diameter. A vacuum would exist above the water in the tube. The slight decrease in air pressure that comes with cloudy weather would cause the top of the liquid column to settle. And clear weather would be marked by a rise.

There are some practical difficulties in the use of the water-column barometer * which are avoided by using the mercury-filled tube. Still more convenient, though less accurate, is the aneroid barometer. When you open a can of vacuum-packed coffee (it's only a partial vacuum), let air enter, and thus

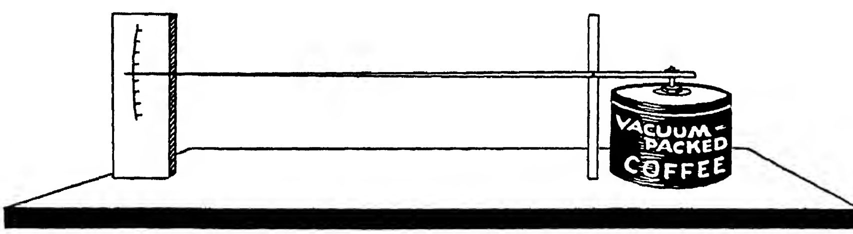


FIG. 13. Aneroid Barometer with Coffee Can.

equalize inside and outside pressures, the elastic metal walls snap out to normal positions. Suppose you had put the unopened can in a larger container and had exhausted the air then surrounding the can. The metal walls would have expanded as the outside pressure was decreased. Indeed, the can does this same thing, though very slightly, as it sits on the grocer's shelf while pressure changes of the weather come and go. The effect can easily be multiplied by soldering a lever's short arm to the can top and making a scale at the end of the long arm (Fig. 13). This is the principle of the aneroid barometer.

The barometer begins to "fall" before the wind and rain occur, sometimes before the sky clouds over. As it continues

* Can you state any of them?

to fall the weather gets worse. Destructive winds are almost certain if the drop is as much as an inch on the mercurial column.

WEATHER MAPS. In the United States are more than two hundred weather-bureau stations, at each of which the atmospheric pressure is read in hundredths of an inch * at the same moment. By telegraph, the readings all may be assembled

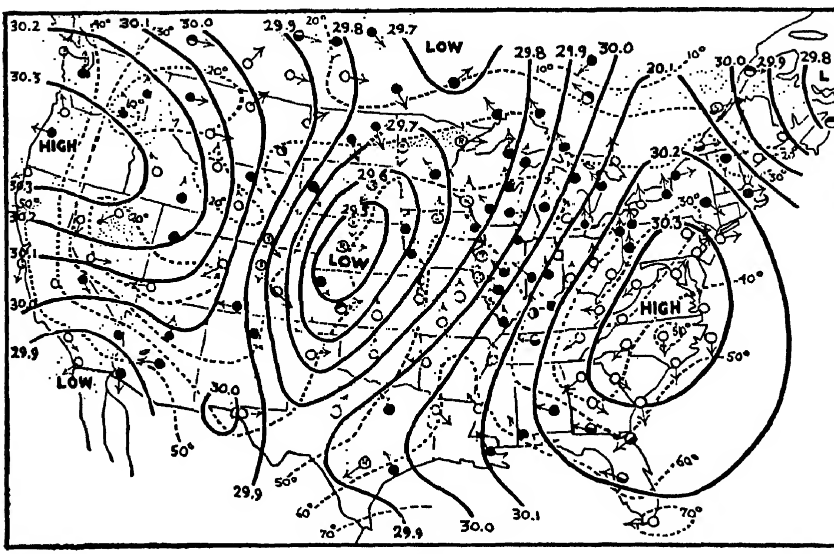


FIG. 14. Daily Weather Map.
Jan. 9, 1939.

Trace the 40° isotherm through the eastern HIGH and central LOW. It's as cold in central Georgia as in Minneapolis, Minn. Or, it's as warm in Minneapolis as in northern Mexico. What explanation have you? (U. S. Department of Agriculture, Weather Bureau.)

in one place within a few minutes and the figures for each station put on a map. This becomes a pressure map of the United States for, say, 7:00 A.M., Central Standard Time, Monday, January 9, 1939 (Fig. 14). It is made more readable by drawing lines on it through all points of the same pressure. The pressure pattern of the entire country is thus portrayed. It

* Average atmospheric pressure at sea level will hold up a column of mercury about thirty inches long.

commonly will show one or two centers of more than average pressure (Highs), grading out into one or two of less than average (Lows). Concentric isobar lines (*iso*, Greek for equal; *bar*, pressure or weight) encircle them. They may have a diameter of several hundred miles.

The same procedure the next morning will yield a different map. When the isobars are drawn, the high-pressure and low-pressure centers will appear farther east. And on the third day they will be still farther east, with perhaps a new High or Low coming into the country from the west, or southwest or northwest.*

HIGHS AND LOWS. Thus the Highs and Lows swing across the continent in the general movement of the prevailing westerlies, bringing cloudy weather when a Low drifts over us and clear weather in the succeeding High. Weather is variable, we know. Reason enough, if the traveling Lows and Highs are scrutinized. They vary in size, they vary in pressure, they vary in rate of travel, they vary in routes followed. Some become weaker as they travel, some develop greater strength. Yet with all this variability, their "habits" make weather forecasting possible. Accuracy will improve in the near future as the meteorologist gets more complete data from the rapidly increasing exploration of the upper air. Hitherto he has been limited to observations made only at the very bottom of the atmosphere.

When wind direction at each station is also plotted on the map, there is seen a distinct inblowing toward the central part of a Low and an outflowing of winds from the center of a High. The immediate cause is obvious but one might wonder why this flow should not shortly equalize the pressures, bring both the Highs and Lows to an end. There is good evidence that in the Lows the inflowing air escapes by rising to higher altitudes,† and that in the Highs cold upper air constantly descends

* Why shouldn't the stations in Colorado, the highest state in the nation, always show a low-pressure area?

† Is this a reason for the cloudiness of Lows?

to feed the outflowing winds. Sometime we shall know enough to explain the "why" of this.

"An east wind brings rain." That's correct, in the sense that an east wind precedes rain. But a low-pressure area really causes the rain and the Low approaches from the west, while the wind is blowing from the east.*

Air rising in a Low has been drawn in from contact with the land. It is warmer than air half a mile or so above the ground, and is also moist. As it rises, it cools and condensation of water vapor in it occurs. Millions of very fine droplets of liquid water may completely fill the sky with cloud; rain may fall because of their coalescence to larger drops. Or, in winter, crystals of solid water (snowflakes) may form directly from condensation of the gaseous vapor.†

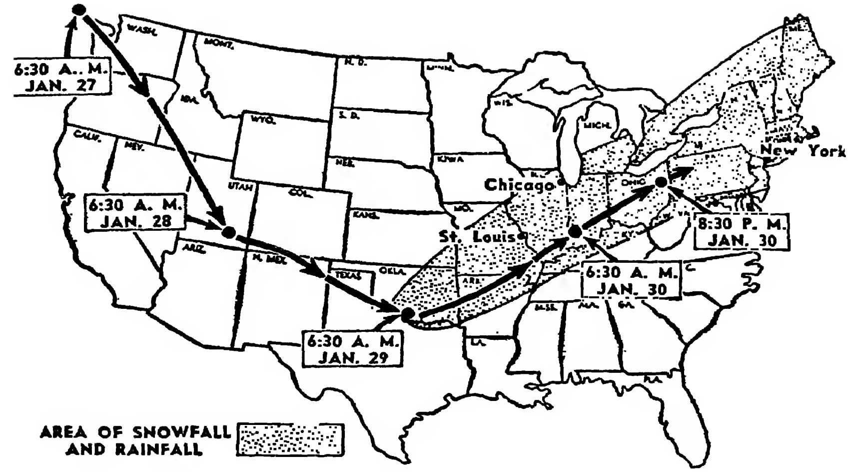
When water is evaporated a certain amount of heat disappears as such ‡ and remains "latent" until condensation of the water vapor occurs. If condensation happens in the rising air of a low-pressure area, the liberated heat warms the air a little and thus enables it to rise a little farther than otherwise would have been possible. This slight warming of rising air as clouds form in it is considered a partial explanation for the persistence of Lows.

THUNDERSTORMS. Thunderstorms are special features of the Lows. Their favoring conditions are found in sharp contacts of warm rising air with colder air above, or in the thrusting of cold air masses from an adjacent High under the warmer air of a part of the Low. Approaching thunderstorms are often heralded by gigantic towering cloud masses (thunderheads), (Fig. 16). By watching steadily for a few minutes, one may see the swelling or boiling out of the upper part of these

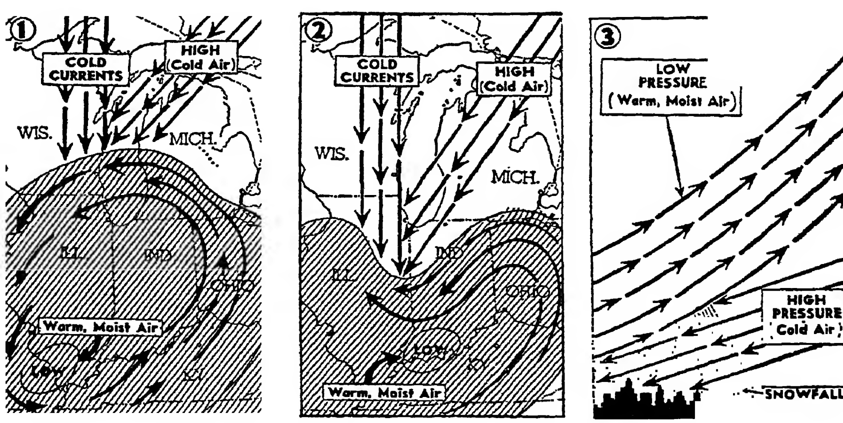
* Can you explain the paradox?

† Close to the ground, cooling of moisture-saturated air may produce fog (identical with cloud except in location) or dew (which "collects," does not "fall") or, if below freezing, frost.

‡ The old woodsman wets a forefinger and holds it up to detect the direction of an air drift too faint to feel as wind. The Boy Scouts learned it from him. How does this trick tell them?



Broken line marks path of the storm across the United States. It started (?) in the Pacific ocean south of Alaska at 6:30 A.M. last Wednesday. Figures on map indicate center of low pressure area and its day by day advance. The shaded area marks limits of precipitation. Snow did not fall throughout the shaded area, but only along the northern margin from Illinois to Maine. Rain fell along the lower edge of the area.



(*Chicago Tribune*, Tuesday, Jan. 31, 1939.) Why Chicago had a storm yesterday. 1. There was a low pressure area (warm, moist air) circling (?) counter-clockwise over the central west, and cold winds from the north and (?) a high pressure area (also cold winds) from the northeast driving a wedge down toward it. 2. The winds met and a dent was driven in the low pressure area as the cold winds pushed under it. 3. The same circumstance in cross section. Cold winds slipped under the low pressure area and the rise chilled the warm, damp air, causing snow to fall.

FIG. 15. A Newspaper Man's Interpretation of What the Weather Bureau Told Him about the Heaviest Snowfall in Chicago Since Measurements Began, in 1871.

Query marks in parentheses are added. Two indicate misstatements, one locates an incomplete statement that needs amplification. One of the misstatements is also shown on the map. To help you, I'll ask what you think of those *two* cold winds from the north.

clouds as the local convection current of moist, warm air is pushed up into much colder air and its water vapor is there condensed. This rapid movement and condensation are responsible in some way for the high-voltage electric charges these

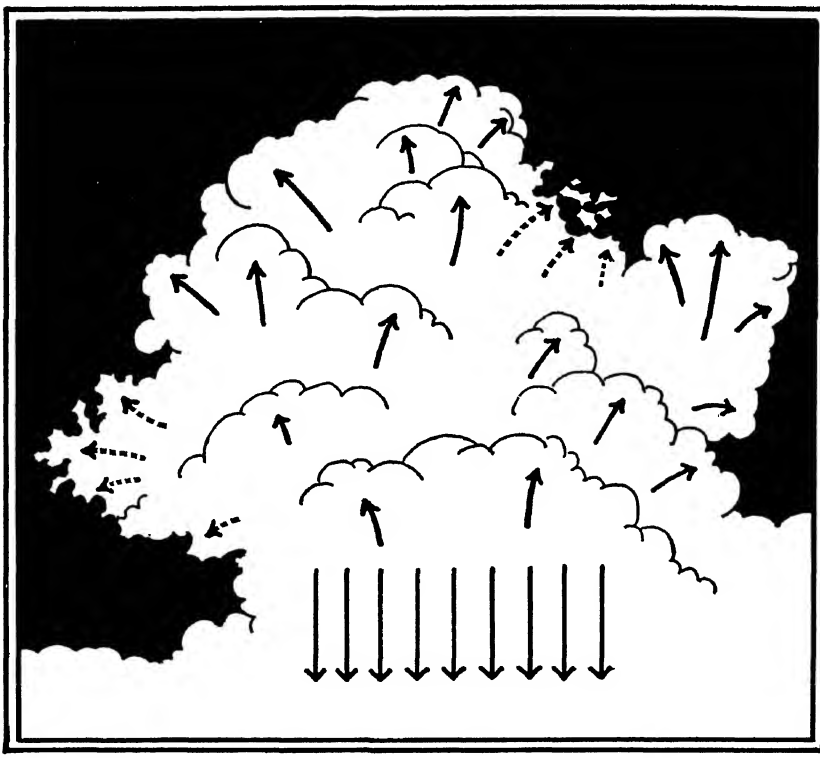


FIG. 16. Thunderhead Cloud (Cumulo-nimbus) with Arrows to Show Rising Air Currents and Falling Rain.

Note ragged outline of the cloud in the two places where arrows are dotted. There's a simple explanation for it. (After Hann, *Lehrbuch der Meteorologie*, Tauchnitz, publishers.)

clouds develop. The weather man can recognize conditions for the making of thunderstorms but can do little yet in indicating just where and when they will occur.

TORNADOES.* From March till late summer, these small, short-lived storms of terrific intensity may strike in the

* In newspaper accounts, they are likely to be called cyclones or twisters.

southern and mid-western states, earlier in the south, later farther north. Their winds spiral inward and upward with the greatest air velocities known, as much as five hundred miles an hour. The tornado's elongated funnel shape, black with rain,* grows downward from the general storm clouds above, sometimes bending and twisting about like a gigantic

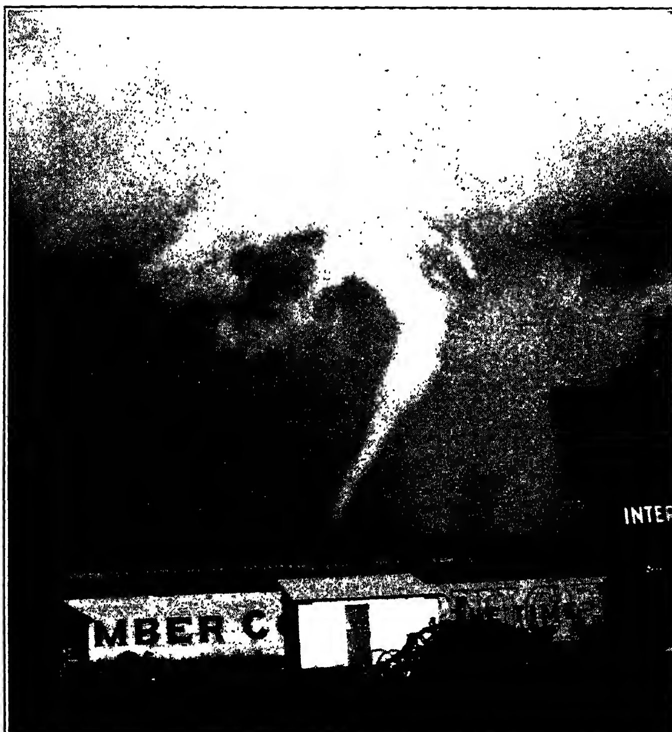


FIG. 17. A fully developed tornado over Nebraska. Owing to unusual lighting conditions, it appears white. (Vac Randa, Photograph.)

elephantine trunk, until it may touch the ground (Fig. 17). Destructiveness is greatest at the funnel tip; almost nothing survives there. Tornadoes may live for an hour, traveling northeastward at a rate far less than that of their own whirling winds. Diameter at the tip may be no more than the width

* It is rain, isn't it, even if it is being carried *upward* by the tremendous air currents?

of a city block; thus, through a forest or built-up area, they leave definite paths of destruction, on either side of which trees and buildings survive intact. At any one place, the destruction is wrought in a minute or less.

Since the tornado is an intense vortex of air, pressure in the interior of the funnel is far less than on the outside, perhaps only a fourth of the normal, and closed houses over which the storm sweeps may literally explode.* Many other aberrant results of tornadoes are common lore; laths and even straws driven through planks, fowls completely plucked but otherwise uninjured, persons stripped of their clothing, corks popped out of bottles, house walls blown away to let the roof fall on the foundations, horses blown away and the wagon to which they were hitched left unmoved, house walls and roof carried off and the kitchen range left with kettle still simmering on it.

Individual tornadoes cannot be forecast. Once started, they move too rapidly across the country to allow warning of their approach to be spread. But tornado-generating conditions are recognizable in advance. Any well-developed Low, centrally located over the Mississippi Valley in spring and summer, that possesses a marked elongation of the southwest half is under suspicion. Meteorologists emphasize the significance of the "wind-shift line" (Fig. 18) which bisects the looped isobars of this elongated part of the low-pressure area. West of the line is southward-flowing air, cold because it is coming from the north. East of the line is northward-flowing air, just arrived from warmer latitudes. Tornadoes are part of the turbulence engendered between these two strongly contrasted, oppositely moving air masses. Half a dozen of them, whirling counterclockwise,† may spring into existence along this wind-shift line, or squall line, live their hectic hour of violence, and die away, all in one disastrous afternoon.

All the features of a tornado's terrific display—winds that leave nothing standing, torrential downpours of rain and hail,

* Which side of a house that is not precisely in the center of the storm path will be most effectively blown out?

† Lay your watch down on Fig. 18 and see.

incessant lightning and thunder, occurring beneath a night-black sky—are but a minor concentration of the results engendered by the quiet sunshine of the preceding days.

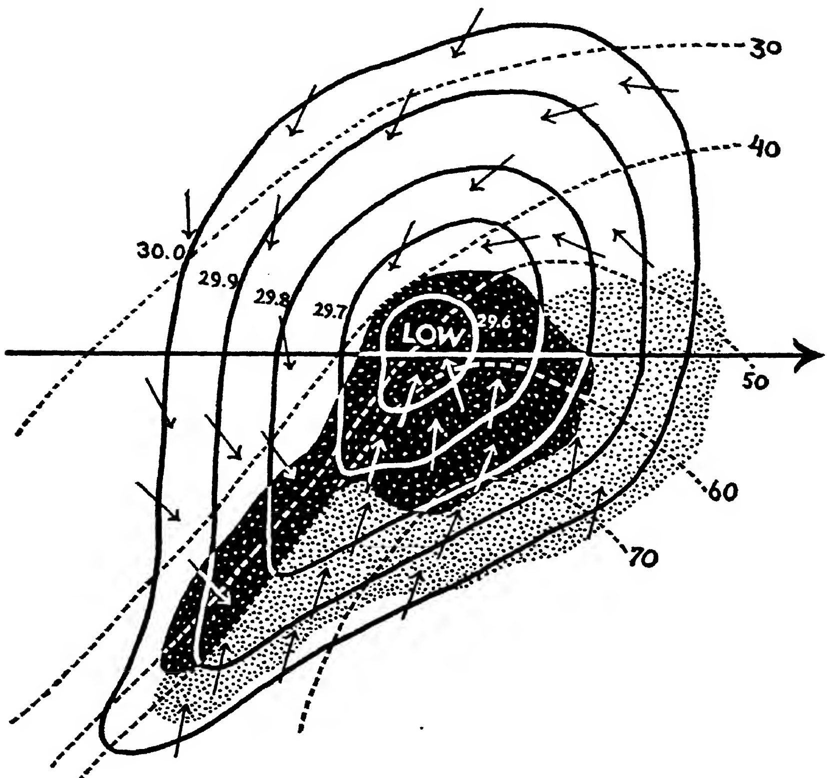


FIG. 18. Wind Shift Line or Squall Line of a LOW.

The line is not on the map. Where should it be drawn? Study the isotherms and wind arrows. The "polar front" is bounded by it. How do you interpret the two differently shaded areas? (Redrawn, by permission of the publishers, The Arthur H. Clark Co., from Lt. Harold L. Kirby's *Analysis of Meteorology as Related to the Operation of Aircraft.*

TROPICAL CYCLONES. In the early afternoon of September 21, 1938, southern New England was attacked simultaneously from the sea and from the air. There were no adequate fortifications for defense. There was no counterattack possible. As though by the massing of an enemy's unopposed navy and air fleet, Long Island and the southern New England coast were laid waste in a few hours.

Though the enemy's presence off the Atlantic coast was known and his general course northward had been reported by the weather bureau for three preceding days, it was a surprise attack. Almost everybody thought he would continue to veer to the right and would leave for the open North Atlantic; few really expected that change in his course, straight north for Long Island, Connecticut, and Rhode Island; and perhaps no one anticipated that threefold increase in his speed during the last twenty-four hours of approach.

The attack was launched at spring high tide.* The weather bureau, watching the storm and issuing bulletins every six hours, had warned of the possibility of a "whole gale" (a mile-a-minute wind), a velocity seldom experienced inland. But by mid-afternoon, wind over southern New England was blowing two miles a minute, with maximal supergusts at Blue Hill Meteorological Observatory, Massachusetts, of 183 miles an hour. The barometric pressure dropped to twenty-eight inches in the storm path, the sea level rose an undetermined amount because of this, superposed on the combined high tide of sun and moon. The biggest waves of a hundred years, atop this astronomical and barometric rise of sea level, crashed into the coast line, the harbors, water fronts, summer colonies. Dragged forward by the terrific wind, salt water surged up over low-lying lands, twelve to twenty-five feet above mean low-water level. The crests of these waves, torn off by the wind, became salt spray that encrusted windows and killed vegetation for twenty miles back from the coast. Traces of salt were found in the deluge of rain for fifty miles inland. Millions of ornamental, wood-lot and forest trees went down; half of all the trees in the storm path. With them went the poles of twenty thousand miles of telephone, telegraph, and power lines. Boats tossed ashore became battering rams, cottages crumpled, roofs kited. More than twenty-five hundred boats were wrecked, many ending up several hundred feet inland. Nearly nineteen thousand buildings were destroyed. A major catastrophe, with

* "Spring" high tide in September, and in the northern hemisphere? Remember this query of yours when you come to "Tides."

six hundred dead and perhaps \$330,000,000 worth of property gone, all in one afternoon's experience with a West Indian tropical cyclone of hurricane violence.

Tropical cyclones invade the United States every summer from the Gulf of Mexico or the Atlantic. About every three years, one of hurricane intensity (wind more than 75 mph) arrives. They originate in the doldrums, either over the western Caribbean Sea or over the open Atlantic east of the Lesser Antilles. Their paths, though irregular, virtually all involve an initial west to northwest course until in the latitude of Cuba

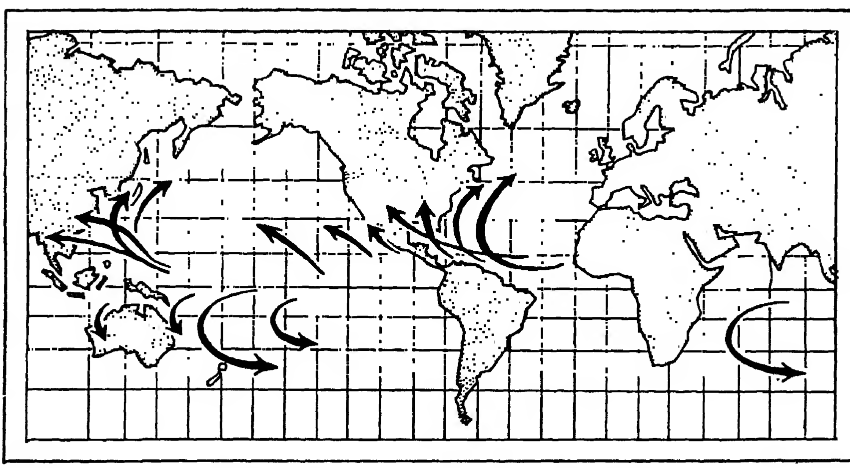


FIG. 19. "Arrows indicate principal world regions of tropical cyclones, and, roughly, the direction of their movement." (From Tannehill, *Hurricanes,* Princeton University Press, 1938.)

and Florida, where they turn to the right, traveling to the north and then northeast (Fig. 19). As many as twenty-one tropical cyclones have occurred in one summer (including early autumn), some of the Atlantic-born ones turning northeast before reaching the continent. They live for eight to ten days, dying finally far north of the place of their birth. They are supposed to be great flat whirls of rising warm tropical air. They are fifty to a few hundred miles in diameter and about a mile high. Wind velocities are greater as the center is approached but—most surprising and still a puzzle to the meteor-

ologists *—these storms have a central "eye" in which the air is calm and the sky clear. In the New England hurricane described above, this eye was about forty miles in diameter. Places directly in the path of the storm center will first have winds from the northeast; then, with increasing velocity, from the northeast-by-east; then, perhaps with hurricane violence, from the east (Fig. 20). Then abruptly the wind will drop, the

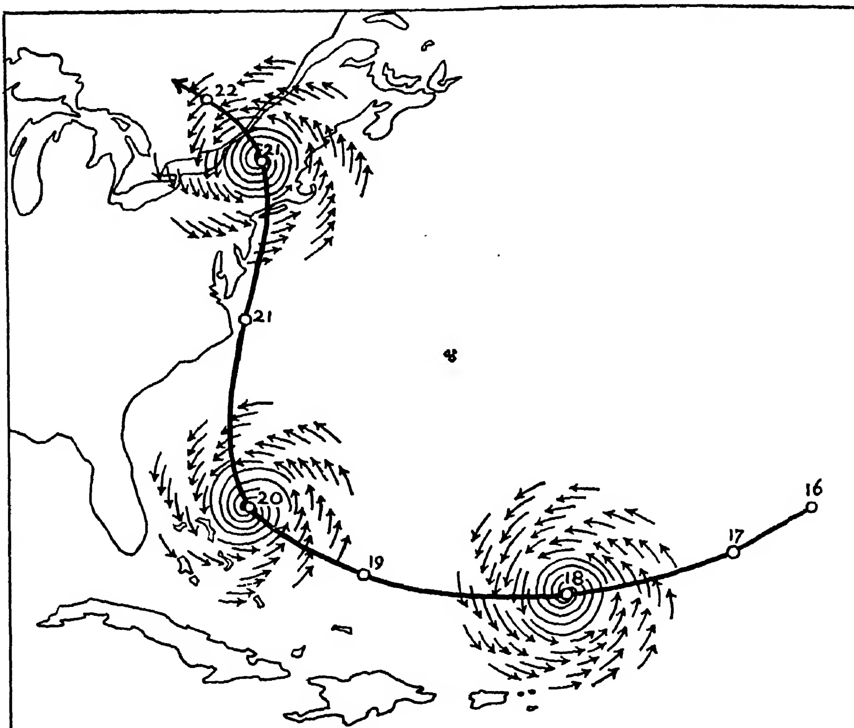


Fig. 20. Course of the New England Hurricane of September, 1938. (After Tannehill, *Hurricanes,* Princeton University Press, and *Monthly Weather Review,* U. S. Department of Agriculture.)

rain cease, the sun or stars shine through. The air is so quiet that an unsheltered match may burn to a stub. Whether the air is rising or descending in this eye, we do not yet know.

* Of course there are theories, and of course they will conflict until we have more facts about the upper circulation of these storms. How do you like a comparison with the swirling of water as it drains out of a wash bowl?

Then suddenly the wind bursts out from the west, again at maximum velocity but decreasing and swinging around to come from the southwest until the storm is over at that place.* To many, this second period of wind means that the storm "came back." Correctly stated, the southern half of the storm arrived.

CLIMATE. Whoever tells you with conviction that "the climate is changing" is probably remembering especially hot summers or unusually cold winters of years ago, or is quoting some oldest inhabitant's memories. It's a thousand to one that he has made no instrumental measurements and kept no written records. His conclusion is based on spectacular extremes recorded in those notoriously inaccurate archives—human memories. And he probably isn't allowing enough time; it should take fifty years or so of observation to determine that composite of weather variations which we call climate. The climate of a region is a complex picture of decades of its weather. In some regions, chiefly equatorial, one day's weather is so nearly the same as every other's that only a few years of observation would be adequate. Increasing latitude brings increasing weather variations, increasing extremes in the chief climatic elements—temperature and humidity. Especially is this true when the westerlies are entered from the trade-wind belts, for here occurs that almost constant succession of traveling Highs and Lows, something unknown in lower latitudes. The wind belts are essentially latitude-bounded, anyway. Thus, the most satisfactory brief delineation of climates of the earth must be based on latitude control. From the effect of latitude (or, more precisely, of what latitude expresses) springs the time-honored concept of five great climatic zones: tropical, intermediate (also called temperate), and polar (sometimes called frigid).†

* No tropical cyclone born in the Caribbean or nearby Atlantic ever has wind rotation in the opposite direction. The principle involved is the same as in deflection of the trades, anti-trades, prevailing westerlies; to the right (of the direct course toward the center it would otherwise take) in the northern hemisphere.

† That makes five.

Factors modifying latitude control are numerous and result in many more than three types of climate. Chief among these factors is the influence of large land areas and large water bodies. Thus there are continental climates and oceanic climates in the same zone, markedly in contrast with each other though in the same latitude and under the same wind system. A continental interior has much colder winters and much hotter summers than do oceanic islands and windward continental coasts, and a greater range in temperature of the daylight and nighttime portions of the twenty-four-hour period. Much less rainfall, also. Compare Montana with western Washington for these points. Spring comes earlier in the continental interior, and autumn more promptly, than in the region under oceanic influence.*

The monsoon climate, well developed along some continental margins in equatorial regions, consists of reversing winds which blow landward in summer and seaward in winter. In each case, the wind is moving from a cooler to a warmer region, and rain is unlikely unless in this movement lower air is forced to rise because of high land farther along the monsoon's course.

Whatever the latitude or wind system, another factor which adds to the variety of climates on any one continent is altitude. It's cooler up in the mountains than on the surrounding plains, and there's more precipitation. Indeed, the plains to the lee of the mountain range (in the rain shadow) may be too arid for any use because the cool mountains "squeezed out the moisture" as the wind crossed them.† The *dry* timber line is the lower limit of rainfall adequate for forests on mountains and plateaus. Highlands also have greater daily and seasonal ranges in temperature than do adjacent lowlands.

* You have already encountered the reasons.

† You'll find large tracts of low rainfall on Fig. 11 that do not lie in the belts of horse latitude calms. Where are they with reference to continents? Are there high mountains upwind from them?

BIBLIOGRAPHY

(The books regarded as most essential are marked with an asterisk.)

* Brooks, C. F., *Why the Weather,* Harcourt, Brace and Company, New York, 1935.

If the changing weather of the seasons awakens questions in your mind, you'll read this book four times.

* Kirby, Lieut. Harold L., *An Analysis of Meteorology as Related to the Operation of Aircraft,* The A. H. Clark Company, Glendale, 1939.

If you have any interest in flying, this book will intrigue you.

Koeppe, C. E., *Weather and Climate,* McKnight and McKnight, Bloomington, 1935.

Written for a purpose different from the purpose of Kirby's book, and full of interesting things.

National Geographic Magazine, National Geographic Society, Washington, D. C., April and June, 1934, October, 1935, and January and May, 1936.

Stratosphere balloon flights sponsored by the National Geographic Society and the United Army Air Corps are described in these issues of the *National Geographic Magazine.* The January, 1936, issue contains, in "Man's Farthest Aloft," Captain Stevens' own account of the flight of Explorer II. The Society has also published full scientific accounts of the flights of both balloons, the "Explorer" and the "Explorer II," in their Stratosphere Series No. 1, 1935, and No. 2, 1936.

Tannehill, I. R., *Hurricanes,* Princeton University Press, 1938.

For more than twenty years Tannehill has been in the hurricane warning service of the Weather Bureau. His book is intensely interesting. It was published just before the New England hurricane occurred, but it will be Tannehill who will give us a full description and analysis when one is printed.

* Trewartha, G. T., *An Introduction to Weather and Climate,* McGraw-Hill Book Company, New York, 1937.

Once you come to understand it, the most atrocious weather becomes interesting. Trewartha will almost make you want to be a meteorologist.

CHAPTER III

THE LIQUID FILM OF THE EARTH

Mobile, though less so than the gaseous film; transparent, though far less so than the gaseous film; discontinuous (interrupted by the continents); far less deep than the gaseous film, yet with immensely greater pressures at the bottom; uncompressed at depth despite the enormous pressures; without continuous troposphere or stratosphere portions; heated at the top and warmest there; nearly ice-cold at the bottom in all latitudes; circulating because of frictional drag of winds, and of differences in salinity as well as because of low latitude heating and high latitude cooling: these are the most marked contrasts between the liquid and gas films of the earth.

OCEAN BASINS. A smooth lithosphere would have given us a four-fourths ocean, no land at all.* Though differences in elevation of the surface of the solid earth are inconsiderable when its diameter is considered, yet they are twice the greatest depths of the liquid film. All the oceanic ponds are tied together; indeed, they make one great continuous ocean in which the continents are really islands.

The ocean is less deep even than the troposphere. It averages only two and a half miles, its known maxima are nearly seven. Its surface, from which we measure most depths and elevations everywhere, stands almost halfway between the highest and the lowest places on the lithosphere. Yet the average elevation of the land above sea level is only half a mile, so the ocean "basins" are much more than half full (Fig. 21).

So far as we know, the earth is unique among the planets in possessing a hydrosphere and in possessing the great pro-

* Like Rupert Brooke's heaven for fish.

tuberances and depressions which, with a hydrosphere of the right volume, make continents and oceans. The maximum vertical range of lithosphere irregularities is about twelve miles, the average about three. How these huge relief features originated, we do not know. Not knowing, we theorize rather freely, perhaps too freely. They were here, though not in present outlines, at the earliest geological date we have. They have persisted, despite remarkable vicissitudes, ever since.

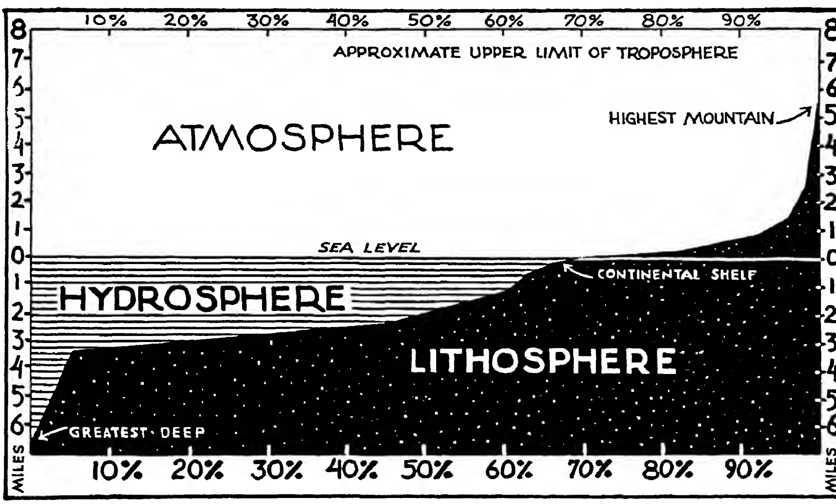


FIG. 21. Diagram to show altitudes and horizontal extent of the greater relief features of the lithosphere. Vertical scale very greatly exaggerated.

That's the fourth dimension of our terrestrial environment, the earth in the past, the dimension of time.

COMPOSITION OF OCEAN WATER. The liquid film is nearly 95 per cent water (H_2O). Let's pause here for a minute. First, what question is raised by that statement? Second, what answer would you make? Stop reading until you formulate an answer. Close the book. Close it! ————————

Water has the ability to dissolve gases. That ability varies with pressure and temperature. Increase in pressure with increase in depth means a corresponding increase of gases in solution. De-

crease in temperature, which goes with greater depth and higher latitude, also means increase of gases in solution. About 2 per cent of the ocean water is oxygen and nitrogen, dissolved from the atmosphere. Then consider the salty, even bitter, taste of ocean water. Dissolved salts! Dilution in tracts of heavy rainfall and large river inflow, and concentration in tracts of high evaporation, make for slight variations in the percentage. The average is about 3½ per cent. So the correct answer to the question you raised is "salts and gases."

Why is the sea water salty? It was a real question once; now we are confident that we know the answer. Fresh water, river water from the land, has made the sea salty. That paradox is due to incompleteness of statement. You are intelligent enough to make a full and consistent statement. It may help to remember that the constant inpouring of river water *does not* freshen the sea.

A logical conclusion flowing from that complete statement is that oceanic salinity can tell us approximately how long oceans have existed on the earth. It's only an estimate but the magnitude of the figures may be surprising. A hundred million years for a minimum!

For making the estimate we may assume: (1) that the sodium (Na) of all salt (NaCl) in the sea has come originally from weathering of rocks on the land, and the chlorine (Cl) from volcanic gases discharged into the atmosphere, (2) that all salt ever contributed is still there, and (3) that the present rate of contribution has been constant throughout geological time. All these assumptions are known to need qualification. From where, for example, have the rock salt strata of New York, Michigan, Texas, Kansas, and other places come, if not from evaporation of ancient lagoons of sea water? Our round hundred million may be far short of a correct answer.

HEATING OF OCEAN WATER. The ocean, reaching from the North Pole almost to the South Pole, gets the same decreasing insolation with increasing latitude which the atmosphere receives. The warmest ocean water is on the surface in

equatorial latitudes. Ice-cold water fills the Arctic Ocean and that great circum-globe Southern or Antarctic Ocean surrounding the continent of Antarctica. Like air, cold water is heavier than warm water. But when cold water sinks because of its greater weight, it is removed from the source of heat, whereas cold air, sinking, comes in contact with the warm surface of the land and sea, is again warmed, again rises. Another contrast—water is only very slightly compressible (contraction by lowering its temperature is not compression), and therefore does not become warmed by compression as it sinks.* Thus there is no universal oceanic troposphere of marked turbulence because of strong vertical currents. Thus, also, the equatorial ocean, averaging 80° F. on the surface, is almost ice-cold in the deep places.†

OCEANIC CIRCULATION. Is there then a thermodynamic circulation in the hydrosphere, comparable to that in the atmosphere? Look at the map of surface ocean currents (Fig. 22). Some warm, some cold, all possessing temperature contrasts with the rest of the ocean they flow in. In what direction (poleward? equatorward?) do the great warm currents flow? The cold ones? Notice that the warm currents generally weaken until they cease, that the cold currents generally cease abruptly where their arrows end. What becomes of their cold water there?

Allowing for irregularities because of shallow depths in some places and complete barriers of land in others, warm water nevertheless generally moves poleward, cold water equatorward. Warm currents start on the surface and stay there. The water of cold currents generally dives under as it enters lower

* It follows that deep ocean water is not denser than surface water, that ships go all the way to the bottom once they sink. Try this on a believer in the popular notion that the Titanic still hovers between the surface and the bottom of the Atlantic, that it never can sink deeper because of increasing density with increasing depth. But perhaps you already know you can't argue with some people.

† Known from measurements, not deductively arrived at. Where does that cold water come from? The surface water is warm and the inside of the earth is hot.

latitudes, enters the great body of cold water which makes up most of the ocean. There is a thermodynamic circulation.

Many complex factors enter into a complete explanation of oceanic circulation; differences in temperature is only one cause. Oceanographers are learning fundamental things about circulation every year. New observations, made by trained scien-

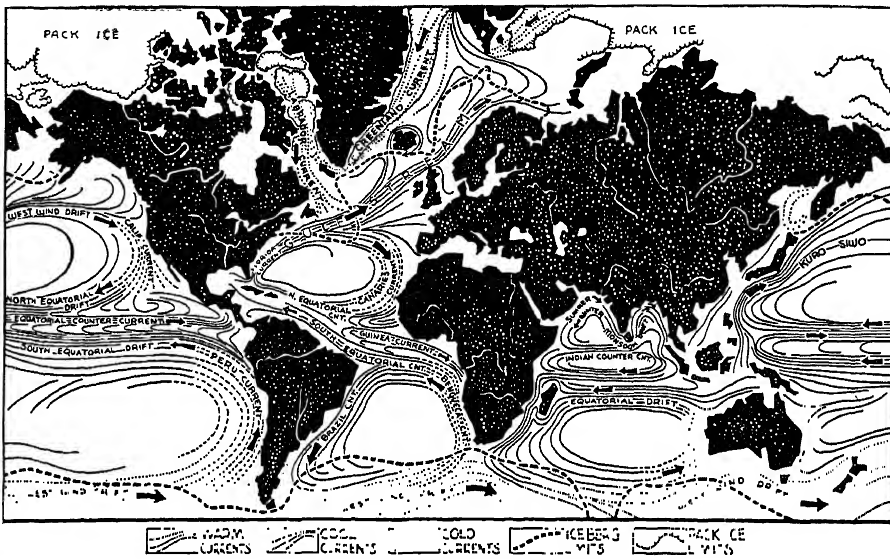


FIG. 22. Map of Ocean Currents.

The great eddies in the North Atlantic and North Pacific flow clockwise, the corresponding ones south of the equator flow contraclockwise. Why shouldn't they be just the reverse?

India's monsoon winds blow northeast and southwest. Why should there be northwest and southeast summer and winter currents in the eastern part of the Arabian Sea?

What explains the occasional appearance of icebergs in the Gulf Stream as far south as the latitude of New York?

Three years, oceanographers think, are consumed in one complete rotation of the North Atlantic eddy. (After J. W. Gregory, "Structural, Physical and Comparative Geography," Blackie and Son, London, 1908, Pl. XI. Bornstein-Bruckmann, "Leitfaden der Wetterkunde," Vieweg and Son, Braunschweig, 1927, Tafel IV.)

tists, of depths, of temperatures and salinity at different depths in the same sounding, are yearly adding to our understanding of the complex oceanic circulation. No book like this can give more than the briefest outline of the subject. No college text, however advanced, can tell the whole of it. No text can be up-to-date in a growing science, and, anyway, textbooks are

never for specialists. Those men discover new things faster than books can be written, or revised.

CLIMATIC EFFECTS OF OCEANS. The oceanic circulation, like the planetary wind system, is a warm-water heating system for higher latitudes. Not alone for the oceans themselves but also for coastal lands lying downwind from the warm currents and drifts. An engineer would deplore the system's low efficiency, the continuous loss of heat as its warm currents flow leisurely toward colder parts of the globe, the chilling effects of cold currents entering warmer seas. The metaphor may not be a happy one, for the system cools as well as heats. Its function is to reduce extreme. In lower latitudes, with too much insolation for man's comfort, enormous quantities of heat are absorbed and taken away by the oceanic circulation. Higher latitudes which are affected by warm currents, receiving this tropical surplus, have warmer winters than their quota of insolation alone would provide. Though some unfortunately situated coastal lands suffer from the close approach of cold currents,* the ocean's circulation warms sufficiently for mankind much more land than it chills.

Even without the pronounced circulation effects, water bodies are equalizers of a region's daily and annual extremes. In tropical desert lands daytime air temperatures of more than 100° F. may be succeeded by freezing at night. Extremes of air temperatures over tropical oceans are in striking contrast. Instead of a range of 60° and more, they are 3° or 4°. And the water itself has a daily range of less than 1°.

Consider also the annual ranges in temperature on land and on water. Siberia is an example of the former, with 25° below zero for winter average and a comfortable living-room temperature of 70° for summer average. This is a range of nearly a hundred degrees, Fahrenheit! The island of Madeira, in the Atlantic Ocean, has an annual range of only about 15°. Most

* Compare Labrador and England, in the same latitude on opposite sides of the Atlantic. It is estimated that 2,000,000 tons of coal burned every minute would not produce the amount of heat brought to Northern Europe by the Gulf Stream.

of the surface ocean water itself varies less than 20° in temperature during the year, whatever its latitude.*

WAVES. Waves on the ocean are very common. Rarely is the surface completely at rest, and never for long. Everybody knows that the omnipresent waves are due to wind, and that the stronger the wind, the larger the waves.† Everybody knows that waves may run beyond the storm, enter calm seas as broad, smooth swells a thousand miles or more from the region of their origin. Does everybody know that waves grow larger (higher and more widely spaced) the farther they travel under the impulse of a constant wind? That no ocean wave crests are more than forty to fifty feet above the adjacent troughs? That waves may under some conditions run faster than the wind that causes them? ‡ That the farther apart the wave crests (i.e., the longer the wave) the faster they travel?

You are watching a particularly big wave approach. It reaches the boat or the pier and a deluge of water is poured over the deck. Is that the water which composed the wave when it was yet a hundred feet away? Or does only the wave *form* travel? Your answer should be prompt—and correct—for you have seen small floating objects simply rise and fall as wave crests and troughs arrive and pass on. It is not, however, a strictly vertical rise and fall. There is a less easily seen forward and backward element in that motion. The floating particles (and all water particles) in the wave are describing circular paths in a vertical plane, like wheels rolling in the direction the wave is traveling, yet staying in the same place and making one rotation with the passage of every wave.

The situation is illustrated in Figure 23, showing a diagrammatic cross section of wave motion at sea. The black dots in

* Would variations in the temperature of deep ocean water be greater or less than this?

† Would you rather ride out a given storm in an ocean of mercury instead of salt water? Would you rather be storm-tossed by hurricanes in an atmosphere of stratosphere, instead of sea-level, density?

‡ After maximum height is reached, the energy of the wind goes into increasing velocity of wave travel.

the surface represent specific particles of water, and the circular path of each is indicated. At the crest of each wave the water is moving in the direction that the wave moves; in the trough it is returning in the opposite direction and rises with the next wave. Thus the water itself does not move far from place. The wave does and the actual energy is in the wave. Each wave moves forward, so to speak, by pushing the water ahead of it. Thus it transmits its energy to the water ahead. In turn, it receives energy from the wave that is behind. There is thus a continuous forward movement of the wave energy by this mutual pushing, although the water itself moves only in circles.

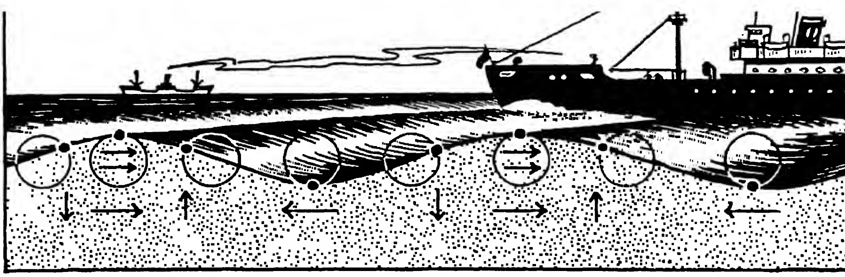


FIG. 23. Movement of Water Particles in a Wave.
Which way are the waves traveling, to the right or to the left?

The "wheels" or orbits of surface particles have diameters equal to the height of the wave. What about particles below the surface, as waves pass overhead? Are they similarly moved? If so, does the diameter of the orbits remain the same, despite increasing depth? Evidence from which to answer this question can be found on the bottom. In relatively shallow water (but several times as deep as the waves are high) mud and sand may be stirred up by the waves, and ripple marks formed.* In deeper water, there is progressively less effect until finally the bottom at sufficiently great depth is wholly undisturbed, even by the greatest storm waves.

The solar energy manifest in waves had to heat the air unequally before winds could occur. Once wind is produced, there is some degradation of energy by friction of air on the

* They are *not* the pattern of the waves themselves.

ground, on the sea, on itself. This slows down the wind and theoretically the energy of motion is changed to heat, which is then lost from the earth by radiation into space. Far more friction results in the water waves, and they die down (when the wind ceases) because and only because of this friction of water particles on water particles. Again heat must be produced,* which later is lost by radiation. The successive steps of activating the gaseous film and, by its movement, of throwing the surface of the liquid film into simple harmonic waves † are dependent on a constant influx of solar energy. The ship, overwhelmed by giant storm waves, is wrecked by the battering blows of tools wielded by the sun.

TIDES. Almost the earliest recorded comments about the sea tell of a rising and falling of the water on its shore, timed to the schedule of the moon across the sky. No lakes had that behavior, only the briny deep. These were the tides. They were under the control of a deity residing in the moon.

Those were good days for simple souls, for everything in nature was so easy to explain. Everybody knew that the moon revolved daily around the earth; it could be seen to occur. Everybody knew that the sun did the same thing. The astonishing denial of that perfectly obvious daily journey, the picture of a rotating earth to explain sunrise, moonrise, star risings, had not been even dimly foreseen. The earth stood still at the center of the universe. It constituted the major part of the universe. Anyone could see that!

The reversal of this early concept, putting the sun in the center of the system and giving the earth a quite subordinate place, did not follow any new and revolutionary discovery of facts. It was simply a more satisfactory way of explaining facts already known. Check this as we go through the next few pages on tides.

* Not that water is sensibly warmed by wave motion. Many significant changes in nature are so slight as to escape our senses.

† It is odd but probably correct to think of air slipping more easily over a wave-covered sea than a smooth one. The waved surface seems to offer less resistance, less friction, to the wind.

The moon's "day" is fifty minutes longer than the sun's. Since our clocks are constructed for the sun's schedule, we say that the moon rises fifty minutes later every night. But it isn't late, it is on time. If the sun's rising and nooning and setting are due only to the rotation of the earth, then this fifty extra minutes of the moon's schedule must mean that it moves in the sky during the day.* It moves far enough to need fifty more minutes to put it where it was in the sky about twenty-four hours before.

If, on the day you start observing, it rises just as the sun sets (full moon), then two days later it will appear on the eastern horizon one hundred minutes (an hour and forty minutes) after sunset. Three days after this, moon rise will occur two hours and a half after sunset.†

But we were talking about tides in the ocean. Today there is a high tide on the beach at (let's say) noon. Yesterday there was a high tide at ten minutes after eleven. Tomorrow there will be one at ten minutes to one. Fifty minutes later every day! The moon's schedule!

Though the tidal schedule agrees with that of the moon, things aren't quite so simple as one might infer from the foregoing. There are *two* highs every day, separated by two low tides. The noon high tide was followed by a low tide culminating about twelve minutes after 6 P.M. Then the water surface rose until twenty-five minutes past midnight for the next high tide. It then sank until about half past six in the morning, again rose to make the ten-minutes-to-one high tide we noted.‡

We ascribe the tides to the gravitative attraction of the moon on the earth. Not that the moon lifts the water bodily or "stretches" it to make the high tide. Rather, it may be said to

* In which direction (east or west) does it move in the sky? You can watch its change of position relative to the stars near it on successive nights.

† There are 1440 minutes in twenty-four hours. How long before the moon will again rise just as the sun sets? This is the time it takes the moon to revolve around the earth.

‡ How many high tides are there on the earth at any one instant? The answer is on the next page or so, but see if you can beat me to it.

pull enough water around the curve of the earth to cause the rise. No water particle moves so very far; it is the cumulative effect of relatively slight shiftings toward the moon that makes the rise. This simple idea will account for one high tide every twenty-four hours and fifty minutes.

What about the high tide midway between? It is midway in space as well as in time. It therefore is on the side away from the moon. Here we can easily get more deeply into theory than we are prepared to go. The oceanographers themselves are still at work on the problem of tides. Instead of a mathematical treatment, we must be satisfied with a picture. To see the reason for the high tide opposite the moon we should get a million miles away from the earth and watch carefully for a month. In that time we would see the moon go completely around the earth in a nearly circular path. What keeps it in that path, that orbit? Both moon and earth are gravitatively pulling on each other. Then why don't they approach each other? Why hasn't the moon long since fallen on the earth? Or we might be looking at the other side of the problem and asking what holds the moon, preventing it from flying off on a tangent as it swings around in that great circle. The two questions, when brought together, answer each other. The same answer applies to the orbital structure of the entire solar system.*

Two opposing forces maintain the earth-moon system intact. If the moon moved faster in its orbit, the tendency to fly off on a tangent would exceed the gravitative grip in which the earth and moon hold each other. If the moon were nearer the earth, gravity would exceed centrifugal force and the two would be drawn together unless the rate of revolution were speeded up. The point of these remarks is that the essential balance of the two forces exists only at the *center* of the earth and of the moon. The side of the earth toward the moon is four thousand miles off center, four thousand miles nearer the moon, and therefore the satellite's gravitative pull on that side actually is

* Kepler, who discovered the laws of planetary motion, was still so close to that earlier unscientific age that he thought each planet was guided and sustained in its orbit by a guardian angel.

greater than the centrifugal force.* On the side opposite the moon, also four thousand miles off center, centrifugal force sufficiently exceeds the moon's pull to allow the bulging up of the tide we were puzzling about (Fig. 24).

Suppose the earth and moon were of equal size and density. Would either one revolve about the other? Wouldn't both revolve about a common center situated half way between them?

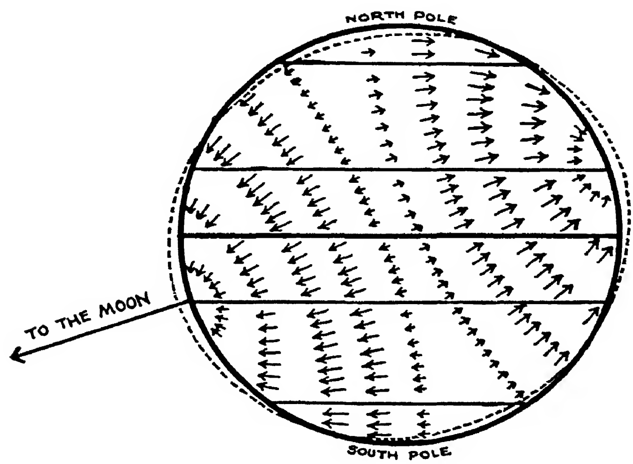


FIG. 24. Tides When Moon Is Vertical over Tropic of Capricorn.

Suppose you are on the tropic, 23½° S. Lat., directly under the moon. Note your tide. Now you ride around with the earth's rotation for twelve hours (add twenty-six minutes, if you insist), until you are on the opposite side (edge of diagram), but not *directly* opposite the moon. Compare the two high tides you have experienced. And didn't you have a low tide between those two highs? Where is it on the diagram?

Where will the moon have to be overhead in the sky to give equal successive high tides? (After Marmer, *The Tide,* D. Appleton-Century Co.)

Suppose one were ten times the mass of the other. Then the center of the system would be correspondingly nearer the larger body. The earth is actually more than eighty times the mass of the moon and the center of the earth-moon system is within the body of the earth *but not at the earth's center.* It is about a thousand miles below the surface on the side toward the moon.

* Don't forget the earth's gravitative grip on itself! The moon isn't going to pull anything *off* that side of the earth.

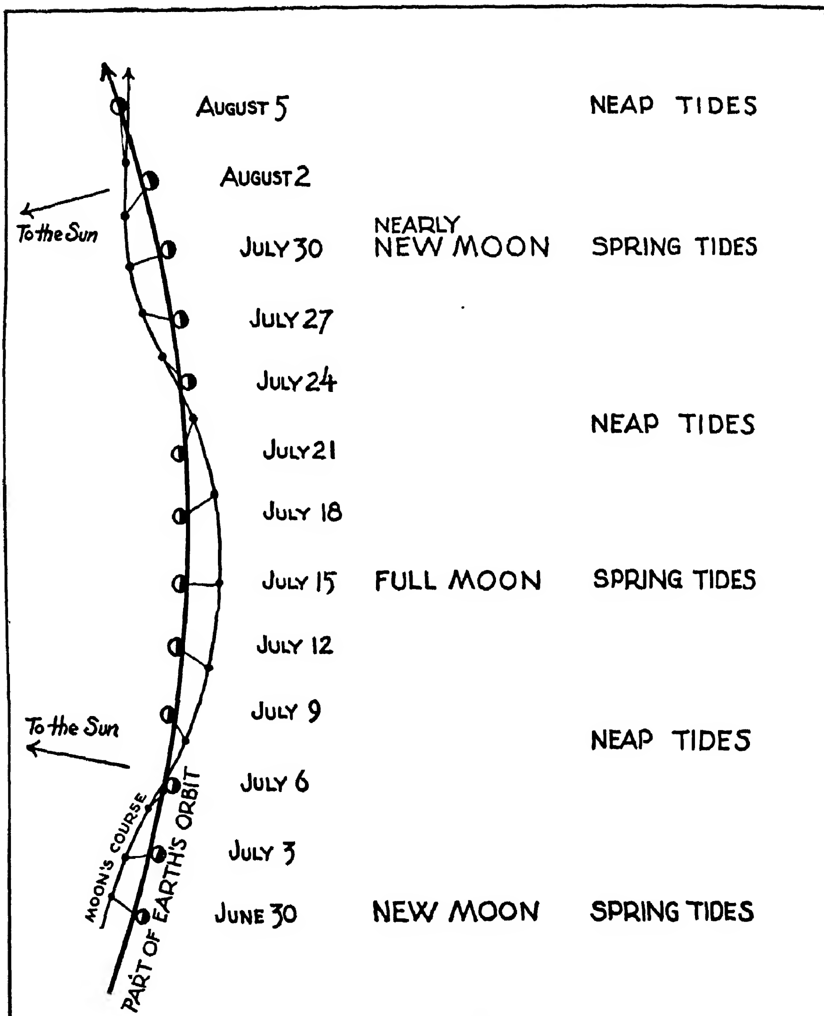


FIG. 25. The Moon's Course as It Accompanies the Earth.

Dates (for one particular year) are for position of the earth.

The lines connecting earth and moon in the diagram indicate moon's position on corresponding dates. The moon actually goes around the earth one and a fraction times on this diagram. Trace it through and see. You will also discover something puzzling about the moon's rate of travel in its course, something for which you will have to go to an astronomer (or his book) for an explanation. The center of the earth-moon system, not the center of the earth, follows the earth's orbit. This is shown by exaggeration, as though that center were outside the earth body, instead of 1000 miles inside. (After Salisbury, *Physiography, Advanced Course,* Henry Holt and Co.)

The earth's rotation makes no difference. The central point of the system must remain on a line connecting the centers of the two bodies. Thus there must be an actual monthly turning of the earth's body on this point, to keep seven-eighths of the earth's diameter opposite the revolving moon. In this may be found an explanation for centrifugal force and a high tide on the side of the earth opposite the moon.*

If the earth had a continuous deep ocean, there would be two symmetrical high-tide bulges and a great belt of low tide around the earth between them. The continental obstructions and constrictions produce many variations from this simple form, both in time of tides and in ranges between high and low. Given three or four factors, nature seems able always to produce extraordinarily detailed variability of the product.

Would you like now to pass judgment on another question regarding tides? If the earth-moon system involves tide-producing forces, should we not expect the same from the earth-sun relations? Remember that the sun, though immensely greater than the moon, is nearly four hundred times as far away. Remember that the earth's radius is four thousand miles. Remember that it is the *differential* attraction of the moon on the near and far sides of the earth that causes the tides. The distance between moon center and earth center is, in round numbers, 240,000 miles. But it is only 236,000 miles between the near earth side and the moon's center. And 244,000 miles between the far earth side and the moon's center. Now consider the *differential* attraction of the sun, ninety-three million miles away, on the two sides of the earth. Four thousand miles off center isn't so important in relation to ninety-three million miles. But, coupled with the hundred and seventy-five times greater gravitative pull of the sun, solar tides *do* occur, less than the moon's tides but definitely recognizable.

* If the moon had an ocean, would it have tides comparable to those of the earth's oceans? Or would they be much less pronounced? Or much more? If you can't answer the question you can at least name the factors involved in finding an answer.

What should the next question be? Will you lift your eyes—right now—from this page until you ask it? ——————

Having asked it and having understood the cause for the moon's tide schedule, you can answer as well as the writer can. The sun's tides must go on an exact twenty-four-hour schedule. There's no fifty-minute falling behind every day. Therefore the tides caused by the two bodies will sometimes coincide, high with high and low with low, while sometimes they will be diametrically opposed to each other, the moon's high offset by the sun's low, and vice versa. At new moon time, when sun and moon are on the same side of the earth, the ocean tides are extra high and extra low (spring tides). Two weeks later, at full moon time, the moon rises in the east as the sun sets in the west. Nevertheless, their tides again are being combined.* It is at "first quarter" and "last quarter," when only half of the moon's lighted disc † is seen from the earth, that the two bodies work in opposition. Then the moon's high tide has the sun's low subtracted from it, and her low is less low because of the sun's high tide at the same place and time. These are the neap tides, occurring also every two weeks and alternating with the spring tides.

CONDITIONS IN OCEANIC DEPTHS. A cubic foot of sea water weighs approximately sixty-four pounds.‡ The bottom of the cube covers 144 square inches and every square inch therefore carries a twelve-inch column of water weighing nearly half a pound (Fig. 26). Thus a depth of only thirty-three feet beneath the surface of the ocean has a pressure equal to that of the entire atmosphere, fifteen pounds to the square inch.§ Small wonder that divers and submarines are strictly limited to shallow depths. Only Beebe in his enormously

* You could have reasoned that out, without being told.

† Of course one side of the moon is always dark. Is it always the same side?

‡ Why specify "sea" water?

§ Sometimes a unit of weight or pressure, as in the expression "ten atmospheres."

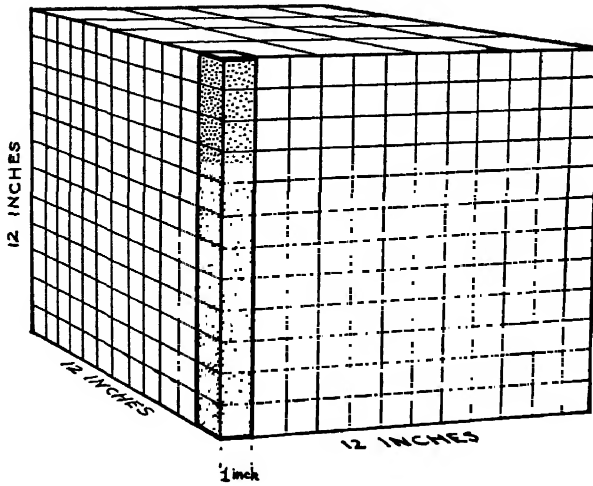


FIG. 26. Nearly half a pound of sea water in each one-foot column, nearly 64 pounds in the entire cube. Pure water weighs 62.4 pounds to the cubic foot.

strong spherical bathysphere (Fig. 27) has yet been able to enter oceanic depths, and he dared go no deeper than 3028

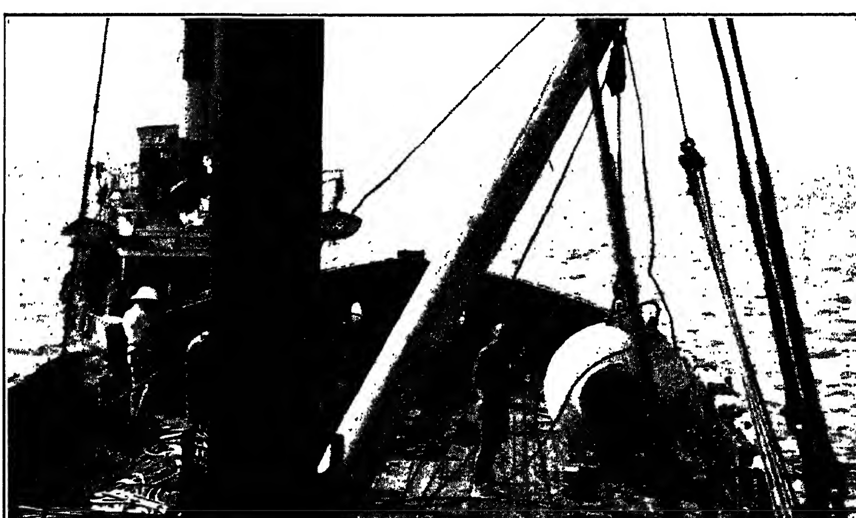


FIG. 27. The two-ton hollow steel sphere that carried two men more than half a mile below sea level and back. (Courtesy of William Beebe.)

feet, little more than half a mile, one-fifth of the ocean's average depth and one-thirteenth of its known maximum depth.

Pressure a mile down is more than a ton to the square inch, and at the greatest depth known (6¾ miles) it is more than seven tons to the square inch. Instruments let down on a piano wire for miles (every thirty-three feet of which means an additional "atmosphere" of pressure) must be specially constructed for the experience. Ordinary thermometer glass tubes are crushed to powder. Blocks of wood sent down come back with every tiny pore water-saturated. They sink like stones after that ordeal. Beebe's bathysphere, let down empty for a preliminary testing, developed a leak and when brought up was nearly full of water. He says, "I began to unscrew the giant wing bolt in the center of the door and, after the first few turns, a strange high singing came forth, then a fine mist, steam-like in consistency, shot out. . . . I cleared the deck in front of the door of everyone, staff and crew. . . . Carefully, little by little, two of us turned the brass handles. . . . Suddenly, without the slightest warning, the bolt was torn from our hands, and the mass of heavy metal was shot across the deck like a shell from a gun. The trajectory was almost straight and the brass bolt hurtled into the steel winch thirty feet away across the deck and sheared a half-inch notch gouged out by the harder metal. This was followed by a solid cylinder of water, which slackened after a while to a cataract, pouring out of the hole in the door, some air mingling with the water, looking like hot steam, instead of compressed air shooting through ice-cold water. If I had been in the way, I would have been decapitated."*

The deep-sea fish live as successfully under these pressures as we do under pressures of fifteen pounds to the square inch. Equilibrium of pressures inside and out is the secret. But let one get too far above the depth to which he is adjusted and he comes *up,* against all his struggles, dying and distorted because of internal expansion as the water pressure decreased.

Life in the ocean is an extraordinarily interesting subject, about which we can make only a few broad generalizations

* *Half Mile Down,* by William Beebe, Harcourt, Brace and Company, 1934, pp. 153-154.

here. The most important factor controlling the forms of life is depth. For with increasing depth comes increasing pressure, decreasing temperature and, vitally important to plants, de-

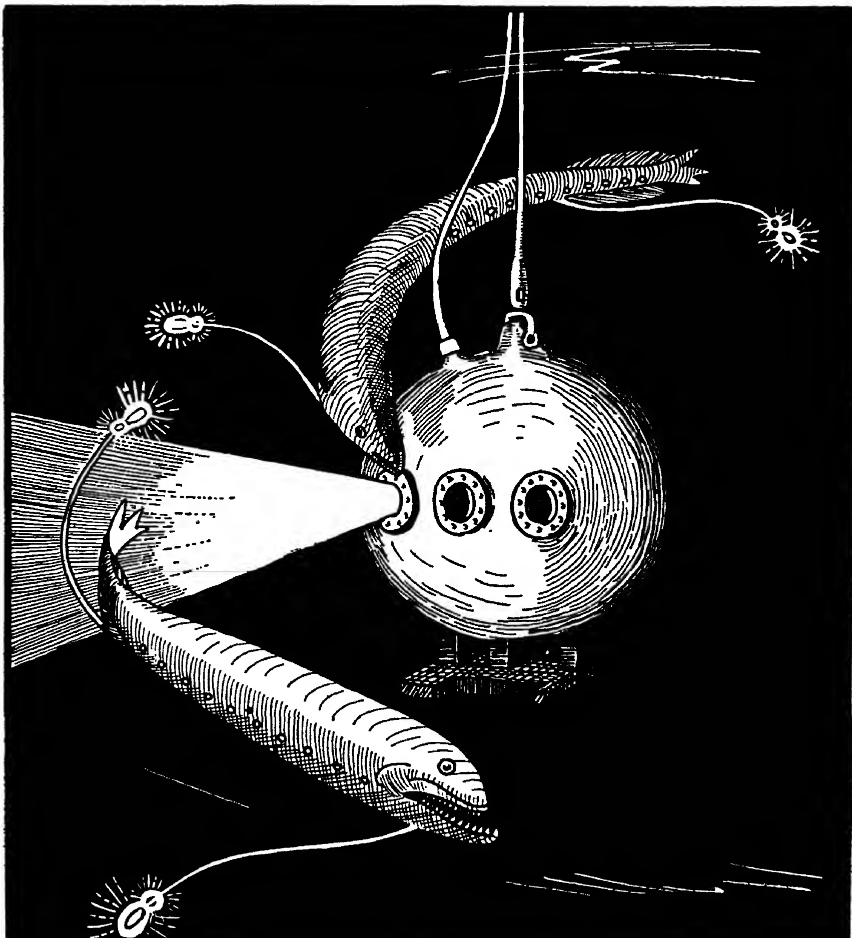


Fig. 28. The lights in rows along the side of the fish are blue. The fore and aft tentacle lights each have two "bulbs," a blue and a red. "Traffic lights," Beebe calls them. (After National Geographic Magazine, p. 677, Vol. 66, 1934.)

creasing illumination to a depth of about three thousand feet, below which is absolute and eternal darkness.

The *photic* zone of the ocean is the superficial sunlit layer. In it live all the green plants, both floating and fixed to the

bottom. A great and varied population of animals is associated with the plants, just as intimately as are land plants and animals. Below the photic zone only animals occur, and these are all scavengers or carnivores preying on them. Food of the scavengers, the remains of dead photic organisms, rains down from above. Many of the deep-sea forms have their own lighting systems, phosphorescent organs exceeding anything of the kind among animals of the earth. Call them "traffic lights" as Beebe did, or defenses, or lures, or what you will, they are amazing. Some crustaceans discharge a luminous cloud of liquid in the face of pursuers. Some of the fish "lights" are carried on elongated tail tips, some on slender tentacles in advance of the head. Some fish are decorated with "constellations" of lights on their flat sides, like rows of illuminated portholes of a ship. Blue and yellow and brilliant red; what puzzles they must constitute for the biologist!

All that which comes to the ocean stays there, except water. Muddy streams flow and dusty winds blow from all the continents. Assaulting all continental margins are attacking waves and the currents they generate. Searching through the rock of the land goes ground water, the devourer of anything soluble. Downgrade moves everything dislodged or dissolved; downgrade to the ocean.

No river current persists very far out from the land, no undertow and no alongshore current reach truly deep ocean water. Current is essential for the transportation of suspended solid particles. Ocean currents themselves do not sweep the shoal water of the coasts, they cannot receive contributions from the land, they do not touch bottom, they do not belong in the picture. It follows therefore that virtually all the mud and silt and sand and gravel of which the continents are being constantly robbed is dropped in relatively shallow oceanic water a few miles or tens of miles offshore. The open sea catches only the wind-borne dust the land has lost.

Probably no one will ever go to the bottom of the ocean and return alive. Certainly no one will ever see the ocean floor through down-pointed telescopes, though it is only a few miles

distant from the surface. We know about it only by our greatly extended mechanical fingers (sounding lines, dredges, samplers) and by electrical ears (echo sounders). Nevertheless the oceanographers have told us more than we would see if we cruised along the bottom in a super-submarine with super-searchlights fore and aft.

The ocean floor is the lowest surface of the lithosphere. Most of it is an enormous plain from two and a quarter to two and three quarters miles below sea level. This ocean bottom plain constitutes nearly half of the entire lithosphere surface. Indented in it are the "deeps," rising above it are continents, islands and the submerged plateaus and mountains our soundings have discovered.

Why should there be any irregularities of the lithosphere surface? Why shouldn't it be a perfectly smooth spheroid? Here is one of geology's problems. It may be that movements in the lithosphere, whereby what may be called great blocks of it have settled or risen, will account for the deeps, the submerged plateaus and mountains. The continents are the greatest blocks of all and are known to be composed of somewhat lighter rock than that underlying the oceans. How they originated is an intriguing question for later discussion. Many small oceanic islands are volcanic cones. Certainly the gradational processes of tearing down the lands and filling up the oceans have in no way aided in making these features.

The ocean floor is covered with mud of unknown thickness, slowly accumulating there since oceans first existed. Its source is atmospheric dust, remains of minute marine organisms, ash and disintegrated pumice from submarine volcanoes.* None of it resembles in composition the familiar mud of fields and roads on the land, nor the mud of lake bottoms or river flats. Its nature points back to different conditions of origin.†

Thousands of mud samples have been taken from all except the Arctic ocean bottoms. About a dozen distinct types have

* Atmospheric dust comes from wind-swept dry lands, from volcanoes above sea level, from the burning of meteorites as they shoot through the air.

† What is the origin of most land mud?

been found, though there are also gradations among these. In distribution, they all show a definite control by the factors of depth, of latitude, and of distance from land. An especially variable constituent of oceanic muds far from land is calcium carbonate (carbonate of lime). It ranges from 50 per cent to more than 70 per cent in the common chalky ooze of average oceanic depths down to 6 per cent or 7 per cent in the red clay common on the deeper floors of all oceans. The source for both is the same; dust, comminuted volcanic material, and the hard, limy parts of (chiefly) microscopic organisms living in the photic zone. All this detritus rains down and is mingled together. A high proportion of organic hard parts produces the chalky ooze. When samples of this ooze are treated with hydrochloric acid and the lime removed, the residue is essentially red clay material. Nature appears to do the same thing during the slow settling of the detritus. The higher pressures of the deep-sea water and its lower temperatures enable it to hold a larger content of dissolved carbon dioxide gas. This takes the microscopic lime particles into solution, leaving almost nothing but the insoluble dust and volcanic ash to reach the abyssal depths and make the red clay deposit.*

Maps of the unseen ocean floor generally depict (1) its topography of deep troughs, extensive plains, submerged plateaus and mountains and (2) its different kinds of deposits.† There are large areas, however, where neither sounding nor sampling has yet been done, where the maps are only good guesses based on the depths and bottom character shown by a few widely separated observations in the region. One goal of the oceanographers, therefore, is more measurements of depth. The vast submarine plains of today's maps are in part expressions of our ignorance. Tomorrow's maps may depict considerable irregularity of that ocean floor.

Sampling of oceanic deposits, which may be done in one

* Where do the organisms get the lime carbonate they build into their hard parts?

† There is no map of either in this chapter. Don't you think one would somewhat resemble the other?

operation with the sounding, has hitherto been limited to the upper few inches of sediment which dredging devices may scrape off. What lay beneath, we could not know. But another goal of the oceanographers is in sight: the sampling of deeper portions of the sediment, earlier deposits now covered by mud of the last few centuries. A gun has recently been invented which, when lowered muzzle-first to the bottom and fired, shoots an open tube straight down into the mud. The tube cuts a cylindrical core, a section of the uppermost few feet of ocean-floor sediment, a record of perhaps the last million years of earth history. Conditions do change, with the passage of time, even on the deep ocean bottoms. These cores, secured out in the mid-Atlantic, tell of four glacial epochs the earth has experienced while the last ten feet of mud have been accumulating, as well as of two epochs of volcanic activity.* This is but the beginning; we shortly will have many more, and probably somewhat longer, cores.

* If the core material was distorted and mixed in the tubes when they were shot down, we would secure no record. Why? And what possible record of glaciation on the continents could be made in mid-Atlantic mud? Would anything on Fig. 22 help you to answer this second question? Perhaps the footnote on p. 163 will help.

BIBLIOGRAPHY

(The books regarded as most essential are marked with an asterisk.)

Beebe, William, *Half Mile Down*, Harcourt, Brace and Company, New York, 1934.

This book contains the material of the two articles listed below and much more. Anything that Dr. Beebe writes is interesting, and he has never had more thrilling trips than these.

Herdman, Sir William, *Founders of Oceanography*, Edward Arnold and Company, London, 1923.

A very interesting book.

Johnstone, James, *A Study of the Oceans*, Edward Arnold and Company, London, 1926.

Though emphasizing geography and geophysics, it comes close to a balanced treatment of the subject.

* Marmer, H. A., *The Sea*, D. Appleton and Company, New York, 1930.

A very good general treatment.

MARMER, H. A., *The Tide*, D. Appleton-Century Company, New York, 1926.

Two hundred and eighty-two pages on a subject to which we give four. If you sail or fish or swim on a seacoast, you'll find plenty to interest you in this book.

MURRAY, SIR JOHN, *The Ocean*, Home University Library, Thornton Butterworth, Limited, London, 1931.

A brief account of the manifold aspects of the subject.

Oceanography, The National Research Council of the National Academy of Sciences, Washington, D. C., 1932.

This is chiefly a statement of research problems.

The National Geographic Magazine, The National Geographic Society, Washington, D. C., December, 1934, WILLIAM BEEBE, *A Half Mile Down*.

The National Geographic Magazine, The National Geographic Society, Washington, D. C., June, 1931, WILLIAM BEEBE, *A Round Trip to Davy Jones's Locker*.

CHAPTER IV

THE SOLID EARTH

INTRODUCTION. Something more than *terra firma,* for the solid earth also underlies the oceans, miles below the lowest level of the land. Something more than the "crust" of the earth, for it constitutes everything below the atmosphere and hydrosphere. The lithosphere is only the outer skin of the solid earth. On its surface we live our little lives, make our little observations concerning air and water and land. But only on the outermost part of that skin! The deepest river-made gash of the world, though awe-inspiring to one on the brink, is cut down only 1/4000 of the distance to the earth's center. The deepest mine penetrates no farther. The deepest well penetrates not quite 1/1333 of the distance to the center. How thick is the rock sphere, the lithosphere? Why shouldn't we consider the solid earth as "rock" to the very center?

Rock is the familiar solid material of the land. Bedrock is consolidated, mantle rock (soil and subsoil) is unconsolidated, but both are solid. There are many kinds of rock but (1) all will liquefy or chemically decompose above 2000° F., (2) very few kinds have a specific gravity greater than three,* and (3) no rock has a crushing strength, or a rigidity, or an elasticity approaching that of steel.

Contrast those facts with the following ones:

1. Temperatures not many miles below the surface are higher than the melting point of any rock.
2. The earth as a whole has a specific gravity of five and a half, and, since that includes the surface rock which averages two and a half, the interior densities must be greater than five and a half.

* Three what?

3a. Earthquake shocks travel through the earth body, below our zone of observation, as though it were a globe of steel.

3b. To the tidal stresses of the sun and moon, the earth body is deformed as would be a sphere of tool steel, rather than one of rock.

A cubic foot of rock weighs approximately a hundred and fifty pounds. At a depth of one mile any cubic foot has 5280 such cubes resting on it, weighing nearly four hundred tons. At a depth of ten miles, 4000 tons (8,000,000 pounds). And ten miles is only one four-hundredth of the distance to the center, and is figured for a specific gravity of only two and a half. So it seems fair to conclude that under the great pressures * in the interior of the solid earth, matter is physically, and probably chemically, unlike that of the skin or "crust." It is like rock only in that it, too, is solid.

Let's drop the word "crust." It suggests the early, and erroneous, idea that the earth's interior is liquid, molten matter. But no sooner have you read this sentence than you rise in challenge. Volcanoes, you assert, have something to say about this! Doesn't molten, liquefied matter, called lava, come to the surface from somewhere in this interior, and doesn't it turn to rock when it cools? Yes, assuredly; to both questions. I'll grant your point, but you must accept my statement about the rigidity of the earth body, proved by seismograph records. How, then, can a proved solid interior yield molten matter?

A wise teacher of my youth used to say that a question mark was shaped so that we, having no answer at the time, might hang it up where it would stare us in the face, a constant challenge to our ignorance, until the answer was found. That's a part of the scientific method. Can you remember an unanswered question as readily as a statement of fact? The solu-

* Pressure at the center, computed from the known size and density of the earth, is 4,000,000 atmospheres, seventeen times the greatest pressures ever attained in any laboratory. Temperature at the center we cannot compute (why not?) but it certainly is far higher than that of any electric-arc furnace.

tion is many pages ahead. We must understand the lithosphere, the surface skin of the solid earth, before we can answer it. To that we now turn. But when we get the answer, you can unhook the query mark and take it down.

Conditions and changes on the land surface are part of our lives, though not so intimately as for the clam-diggers. Portia's "gentle rain from Heaven" is but one kind of rain, and even it may be an insidious thief of the soil. Torrential downpours are outrageous robbers. The placid meadow brook may overnight become an enemy. The Mississippi in flood may escape our control and wreak damage amounting to millions. Coastal fortifications at harbors are ever necessary against the sea. The unstayed march of wind-driven sand may block highways and railroads, may bury farm land. Predatory winds swoop down in drought-stricken areas and carry off enormous quantities of topsoil as dust. An understanding of the whole problem of droughts and winds is essential, if we are to hold such regions for agriculture. Our need of water for irrigation, power, and inland navigation requires an understanding of streams. City water may come from wells; ground water circulations must be understood. For the world's greatest source of power today, we must know the geology of coal. The diminishing reserves of oil and natural gas demand a knowledge adequate for finding new pools and for economical recovery from older ones. The enormous use of metals by civilized man requires specific geological knowledge of the occurrence of their ores. Exhaustion of cultivated soils demands, for one thing, the application of mineral fertilizers; and the geologist must find the lime and phosphate deposits needed. Many non-metallic mineral resources which are vital in modern industry are discovered and exploited by men versed in the principles of geology. The vast structure of our civilization stands on a foundation constructed by science; a knowledge, an ever-growing understanding, and an ever-increasing control of our physical environment.

MAPS. Map-making is probably as old as picture-writing. Early attempts were simple and dealt with small areas. Land

distances were measured with rods, the way you use a yard stick. Distances on the water were measured by "days of sailing," long land distances by "days of marching." The world of Phoenician, Greek, and Roman history centered about the Mediterranean, which is several times as long (east-west) as wide (north-south). East-west distances therefore became

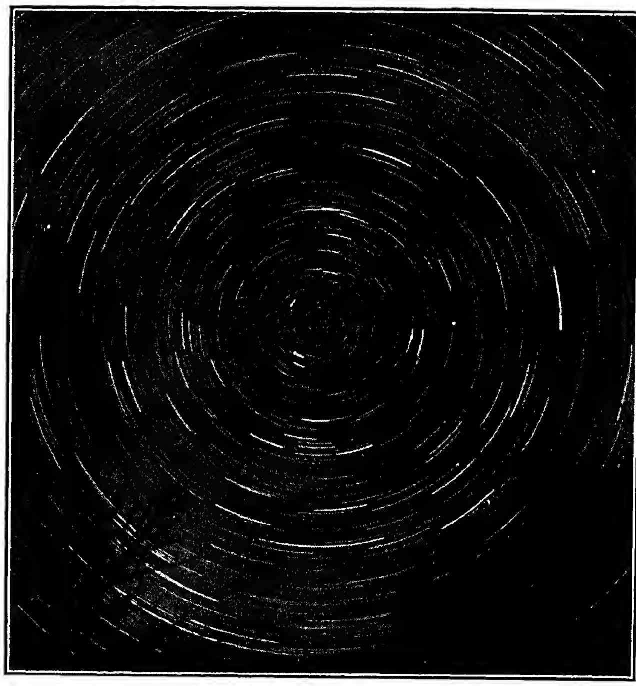


FIG. 29. Star Trails around Polaris.

The pole star clearly is not exactly in line with the earth's axis. About how long an exposure did the picture have? (Courtesy of Yerkes Observatory.)

longus (length), and north-south distances, *latus* (width), terms we use today in modified form. It was not suspected for centuries that north-south lines were not parallel!

When the compass came to Europe * and ships dared venture beyond sight of land, the known world rapidly grew much larger. Shortly it became obvious that north-south directions at points placed well apart in Europe and the adjacent

* From China.

Atlantic were not parallel but converged toward the north. The well-founded suspicion was born, and grew, that man's enlarging world was not flat but curved, a part of a spherical surface. *Longus* of the early Mediterranean navigators became longitude; *latus*, latitude. When trigonometrical methods could be applied (that must needs wait for the invention of the first surveying instruments), the day of tape-measure and day's-journey methods vanished. Exact distances north and south became known across wide regions, for Polaris, the North Star,

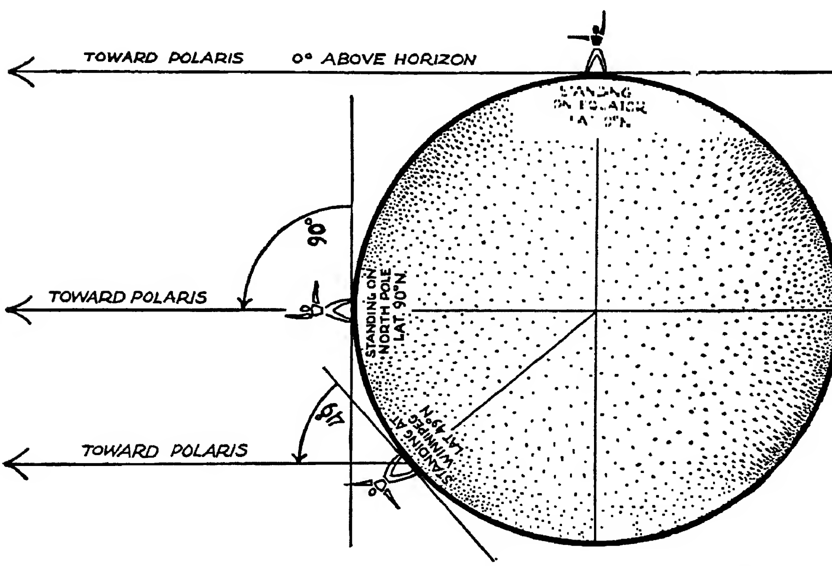


FIG. 30. Altitude of Polaris above Horizon Is Latitude of Observer.

never rises, never sets, never moves in the sky * (Fig. 29), and its altitude above any horizon is always the latitude of the place (Fig. 30).

But how to measure east and west distances on a curved ocean! That required the invention of a very accurate clock, a chronometer (*Chronos,* Grecian god Time). Chronometers are still necessary on ocean-going ships without radio. Any noon, by sun time, is noon only for those places on one north-

* Even if you didn't know that before this instant, I believe you are intelligent enough to explain it.

south line, one meridian. It is already after noon to the east of this line, not yet noon to the west. Now "east," extended on and on, becomes "west," returning to the starting point on the globe, completing a circle. This circle "circles" completely around in twenty-four hours, every point on it running the gamut of evening, midnight, morning, to another noon. If we could fly west as fast as the earth rotates to the east we would stay in the "same place" while the earth turned around beneath us. Every instant of that twenty-four-hour flight would have been *noon,* yet our chronometer would have run off every hour of the twenty-four. If our clock, set for sun time, travels east or west, it must be corrected for sun time of the new location.

But the ship's captain doesn't correct his chronometer. What he wants is the difference between its readings and the sun time of his new location. Let's say that at noon (by the sun) the chronometer reads 11 o'clock. It has run off only 23 hours since the voyage began. Noon has come an hour earlier than if the captain were still in port. Has the ship been sailing east, or west? 360 divided by 24 equals 15. The captain is exactly 15° of longitude east * of where he started.†

A good map must possess the very minimum of distortion. Every east-west mile on it should equal every north-south mile. But the earth's surface is not flat like the sheet of paper on which the map is made. Every continent, every ocean, has a convex surface which, when flattened down to a plane, must inevitably become distorted. For small areas, the amount of curvature is so slight that this distortion becomes negligible. But for larger areas, map "projections" must be used, devices which reduce the distortion in one way or another.

The Mercator projection (Figs. 8, 11, 22) is constructed as though the earth were a cylinder open at the ends. Distortion of both shape and size is enormous in high latitudes, for all parallels of latitudes are shown as of the same length, all meridians as equidistant from each other in all latitudes. The

* Why not west?

† Make a diagram to show.

orthographic projection (Fig. 31) is the eye or camera image of a globe when seen from a distance several times the globe's diameter. It is what the earth would look like from the moon. It must involve distortion around the margins where the spherical surface curves away from the observer, where the meridians and parallels, because of foreshortening, appear closer

FIG. 31. Orthographic Hemispherical Projection. (After Unstead and Taylor, *General and Regional Geography*, Geo. Philip and Son, Ltd., London, 1922.)

together than in the middle of the map. Lambert's equal-area projection (Fig. 6) avoids some of this distortion by spacing the meridians equally along the equator, the parallels equally along a north-south mid-line. But it depicts the parallels as curved, more and more toward the poles, and thus does distort areas, despite its name. The homolographic projection is truly an equal-area plane map of a hemisphere, for the paral-

lels are drawn as straight lines while Lambert's equal spacing of meridians and parallels is retained. Goode's modification of the homolographic projection is shown in Fig. 32. Greenland, which on the Mercator projection is shown as larger than South America, comes down to its true proportions, less than one-ninth as large. The homolographic projection also shows shapes of continents and ocean basins in low latitudes almost as well as does the only ideal world map, a globe.

An ordinary map shows two dimensions, length and width. It is a plane, and it represents a "plane." That may be satisfactory for the ocean but it falls short when lands are depicted. Can a flat map represent the third dimension of land, the vertical, the relief? You have seen caterpillar-like mountain ranges crawling on some maps, and you answer "yes." Then let me ask if, from such a map, you can learn how high this ridge is above that valley, how steep this slope, how wide that canyon at the top, or bottom, or at mid-depth? Can a surveyor lay out a tentative railroad or highway route across a mountain range from such a "hachured" map, tell where he must have switchbacks and zigzags, how many, how long, how steep they must be, where tunnels must be driven? Can an engineer plan the location of dams, of irrigation canals? Can he know the gradient of the river in feet per mile? The answer is no, for the hachure method is little better than a pictograph, and for the needs above listed we must have fairly detailed precision.

There is another method, however, and an excellent one, for showing relief of the land. Let's approach it by considering some sea coast (or lake shore), with many irregular bays separated by peninsulas. That twisty, crooked contact line of land and water is perfectly regular in one respect, however. It is *level!* On the map of this, or any other coast, the shore line represents a level line, all points in it at mean sea level (or lake level).* Now suppose that the sea or lake level rose ten feet. A new horizontal line, probably as crooked as the

* Of course the shore of the Mississippi River won't do.

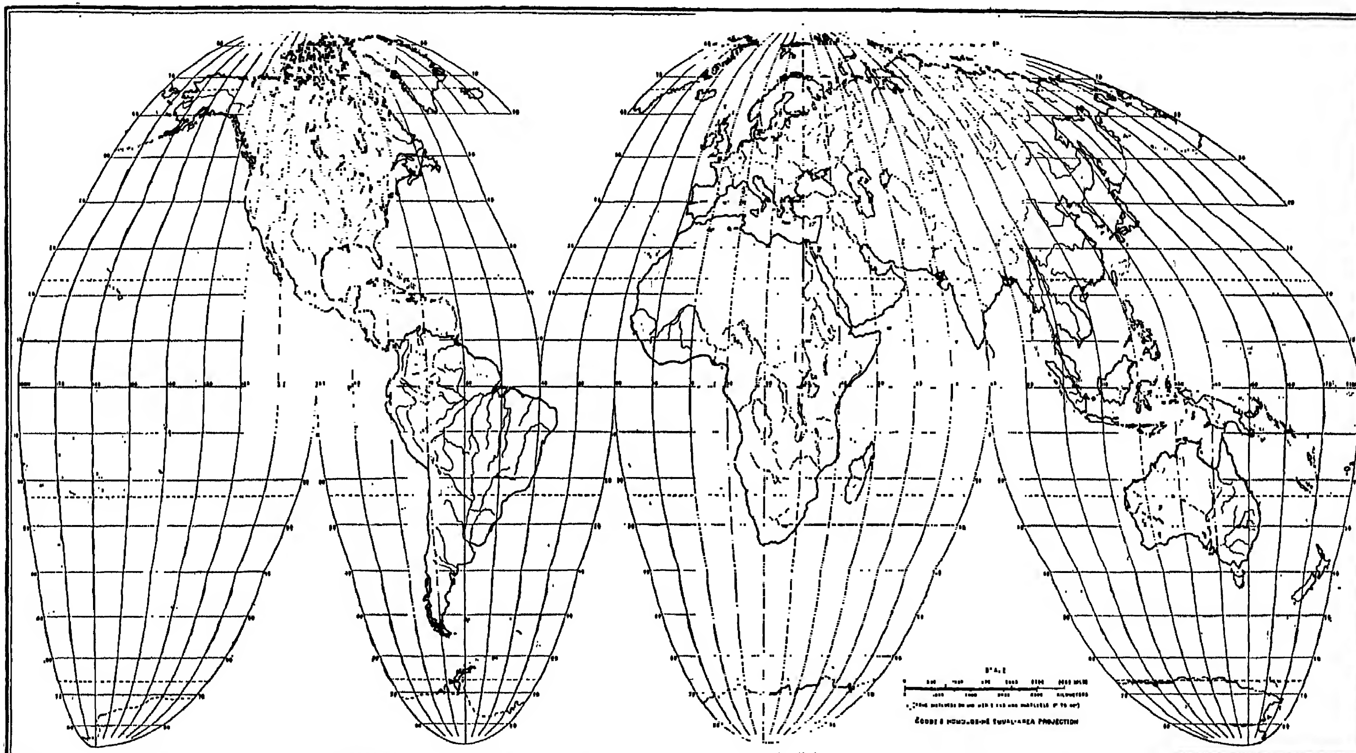


FIG. 32. Goode's Homolosine Equal-Area Projection. (After Goode's Series of Base Maps, No. 201HC, University of Chicago Press.)

original one, would be determined. Suppose it then rose ten feet more. Another line would result, every point in which would be at the same level. Then another ten feet, and so on, until the area was entirely covered. The lines, however ir-

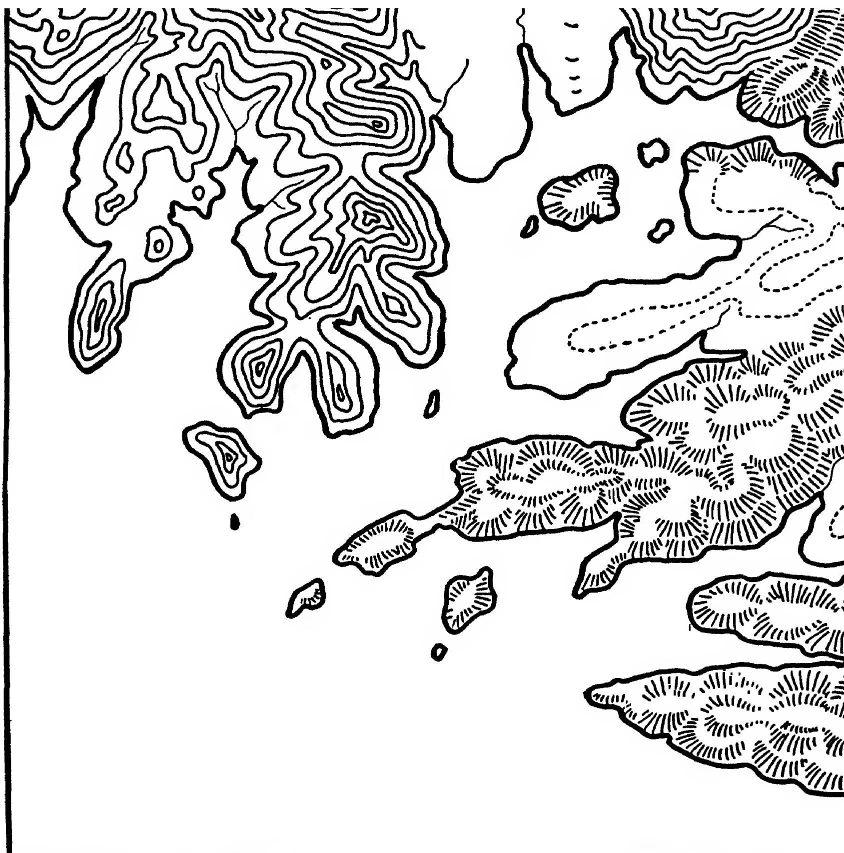


FIG. 33. A Drowned Coast Line.

Two methods of depicting the relief of the hilly land have been used, contours in the northern part, hachures in the eastern. Try your hand at completing them in the unfinished parts of the map. (After Davis, *Atlas for Practical Exercises in Physical Geography*, Ginn and Co.)

regular when looking down on them from the air, would all look horizontal if seen from shipboard off this coast. They are contour lines on the land itself, with a vertical interval of ten feet, and a map of them is a contour map.

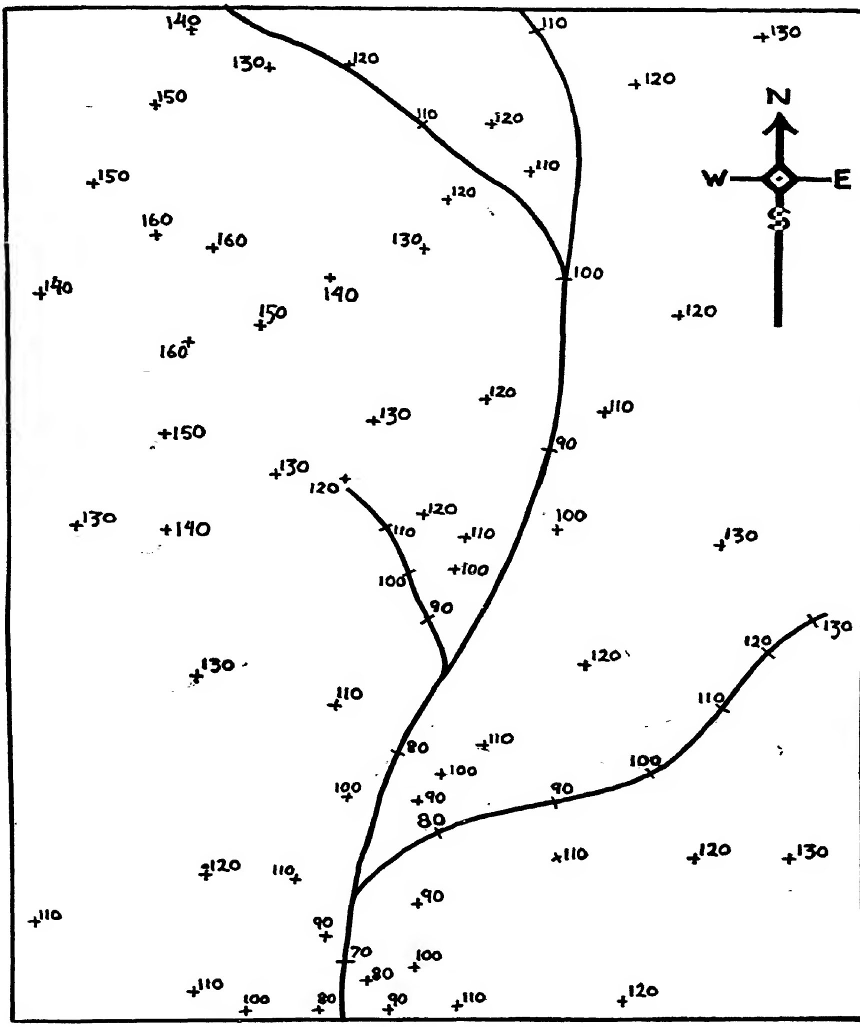


FIG. 34. Data for a Contour Map.

The area shown is about 3 miles wide and has a relief of 90 feet. Its topography is the erosional result of running water.

Suppose you started at altitude 100 on the main stream and, by walking along the west slope of the valley, kept at the same altitude while you traveled "downstream." You would find yourself higher and higher above the stream though not an inch higher above your starting point. Draw a line showing your course southward until you approach the short tributary entering from the west. Here, to stay on the 100-foot contour, you must detour back up the tributary valley but, since its gradient is much steeper than that of the main stream, you haven't far to go before you can walk back again to the larger valley. Do the same with the 90-foot and 80-foot altitude marks. Remember that the slopes are toward the streams, that contour lines never end except on map margins, never branch, never cross each other, that they must run *along* the slopes, that they loop back up the valleys and swing out from higher land to go around hills and ridges. Now, complete the map.

If the land being submerged had river valleys leading to the sea, with hilly divides between the valleys, the rising sea would reach farthest inland along the valleys, "drowning" them, making bays and estuaries of them, and the divides would become peninsulas. In other words, contour lines loop back up valleys from lower country, and they bend out toward lower country to get around higher land just as the shore line on the irregular coast bends seaward where hills stand close to the water (Fig. 33).

If the land sloped very gently and evenly, say ten feet to the mile, these contours on the land would be a mile apart. Then if you mapped this region on a scale of a mile (of land) to an inch (of map), the contour lines would be an inch apart. On steep slopes, the lines would be close.*

Obviously, the making of contour maps doesn't require this hypothetical flooding. Enough altitude measurements with the spirit level,† then the correct placing of these altitudes on the map, then the drawing of lines to connect points of the same altitude, and there is your contour map (Fig. 34). If the region is a plain, with low relief, contours may be drawn at vertical intervals of five to ten feet; if mountainous or deeply canyoned, the interval will have to be larger.

From contour maps may be determined, in part, the feasibility of proposed traffic routes, of hydraulic engineering works, of military operations. For the appreciation and understanding of a region's land forms, they are essential. About half of the United States is now so mapped. Your region may have such a map. The Director of the U. S. Geological Survey, Washington, D. C., can tell you.

* On maps of vertical cliffs, you'd have to draw one on top of the other—but there are very few truly vertical cliffs.

† Spirits (alcohol) instead of water in the sealed tube (there's a reason for alcohol in cold weather), and a bubble to indicate when it is precisely level.

BIBLIOGRAPHY

(The books regarded as most essential are marked with an asterisk.)

BARTKY, WALTER, *Highlights of Astronomy,* University of Chicago Press, 1935.

The calendar, the solar system, solar, sidereal, and standard time, the international date line, and many other things we touched or closely approached in this book are engagingly set forth in *Highlights of Astronomy.*

DAKE, C. L., and BROWN, J. S., *Interpretation of Topographic and Geologic Maps,* McGraw-Hill Book Company, New York, 1925.

More than half this book is devoted to lists of United States Geological Survey contour maps which show various land forms we treat in the present book and to discussion of the selected maps.

* FINCH, V. C., and TREWARTHA, G. T., *Elements of Geography,* Chapter 3, McGraw-Hill Book Company, New York, 1936.

Various projections not mentioned in the present textbook are discussed. Trewartha's *Introduction to Weather and Climate* is a reprint of about half of *Elements of Geography.*

* LONGWELL, C. R., KNOPF, A., and FLINT, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology,* Chapter 1.

One of the most popular college textbooks now in use.

LORD, RUSSELL, *To Hold This Soil,* United States Department of Agriculture, Miscellaneous Publication 321, Washington, D. C., 1938.

A dramatic story, dramatically told. If you liked de Kruif's *Hunger Fighters, Microbe Hunters,* and *Men Against Death,* you'll like this book.

RAISZ, ERWIN, *General Cartography*, McGraw-Hill Book Company, New York, 1938.

It has three chapters (36 pages) on the subject of projections and three chapters on methods of depicting relief.

SALISBURY, R. D., and ATWOOD, W. W., *The Interpretation of Topographic Maps,* Professional Paper 60, United States Geological Survey, 1908.

It contains hundreds of contour maps in three colors, illustrating typical land forms. Now out of print, but to be found in many libraries.

SHARPE, C. F. STEWART, *What Is Soil Erosion?* United States Department of Agriculture, Washington, D. C., Miscellaneous Publication 286, 1938.

Mostly photographs of the multitude of ways our soils are vanishing. Sharpe is also author of a book devoted entirely to one of these ways—landslides. He knows his subject.

The United States Department of Agriculture has issued numerous pamphlets on the soil-erosion problem in different parts of the United States and on methods of prevention. The Secretary of Agriculture will send you the list.

CHAPTER V

STREAM WORK AND STREAM HISTORIES

Source. A cylindrical cup, set up out of doors, has an inch or so of water in it after a hard rainstorm. Thus "an inch of water" fell during that rain. Catching and measuring every rain for a year, the gauge at Chicago averages 33 inches, at New York 43 inches, at New Orleans 57 inches, in desert Nevada 4 inches. If none of it evaporated or sank into the ground or flowed off the surface, in a few months' time we'd live in boats or drown, and eat fish or starve. But the land has slopes and gravity won't let the water stand. Which way does it slope? Almost universally it slopes toward the ocean, continuously downward by however devious a route. On these slopes the water "runs." Without such slopes, it "stands" in lakes and marshes.

Streams and valley-making. Water running off a plowed field is invariably turbid. With it and in it are going millions of mud particles, sand grains. The field left unused for a season or so may become a fretwork of tiny gullies, each rivulet of the runoff having trenched a few inches deep along its course (Fig. 35). If left uncultivated for a decade, some of these gullies may then require an extra long step or a jump to cross them. They are growing, in a tree-like pattern with the trunk downhill, the branches lying farther upslope and the twigs or smallest water courses lying near the top of the slope.

Adjacent to the abandoned plowed field may be a pasture, its slopes the same, its rainfall the same, its soil the same, but its runoff far less turbid and its wet-weather water courses hardly recognizable when the pasture is dry. The grass cover

is the answer; or the forest cover on the woodland area, also adjacent and also ungullied.

We have examined less than a square mile of land. Look at the entire country, as shown on a good map. The crooked blue lines are the creeks and rivers, and their pattern is also rudely tree-like, small ones converging to larger. They flow in trenches much larger than the field rivulets possess, in ravines and valleys. They flow throughout the year, though dry

FIG. 35. Soil Erosion.
One hard rain caused all this miniature gullying. (Courtesy Soil Conservation Service, U. S. Department of Agriculture.)

weather notably decreases their volume. They are muddiest when swollen, after rains. They roll pebbles along their courses in flood time, dropping them in gravel bars when the volume decreases, picking them up again to go farther downstream in the next flood. Even if no one ever saw these ravines and valleys grow, as we did the gullies of the plowed field, they surely have been made the same way. Running water, in large concentrations (large streams) and working for a long time, erodes large trenches (canyons, gorges, valleys) in the surface of the land.

Suppose we challenge this. Suppose we say that the Grand Canyon of the Colorado, a mile deep and fifteen miles wide at the top, is too large an order for running water. We prefer to think that some cataclysm split the plateau open here, and the great chasm of that mighty earthquake became, naturally enough, a discharge route for runoff of the region. Then we

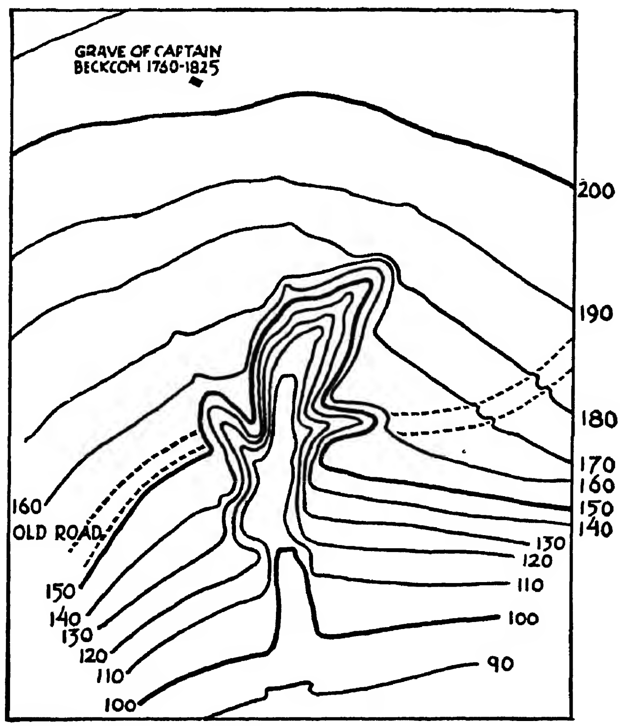


FIG. 36*a*.

FIG. 36. Contour Maps of "Lyell" Gully near Milledgeville, Georgia. (*a*) The gully in 1846. (*b*) The gully in 1937.

must argue that the Little Colorado likewise found its valley ready-made. So did the Virgin River, the San Juan River, and other encanyoned major tributaries. So, likewise, did all the smaller tributary creeks since their valleys are also great clefts in the flat-lying stratified rocks that constitute the plateau.

But quakes occurring under human observation rarely

made open cracks in solid rock and never of a magnitude remotely approaching these canyons; the pattern of rock fractures in quake-ridden areas is parallel or crisscross, never tree-like. These canyons nowhere cross each other. Every one peters out toward higher land, becomes more capacious in a downstream direction, has in that direction a continuously

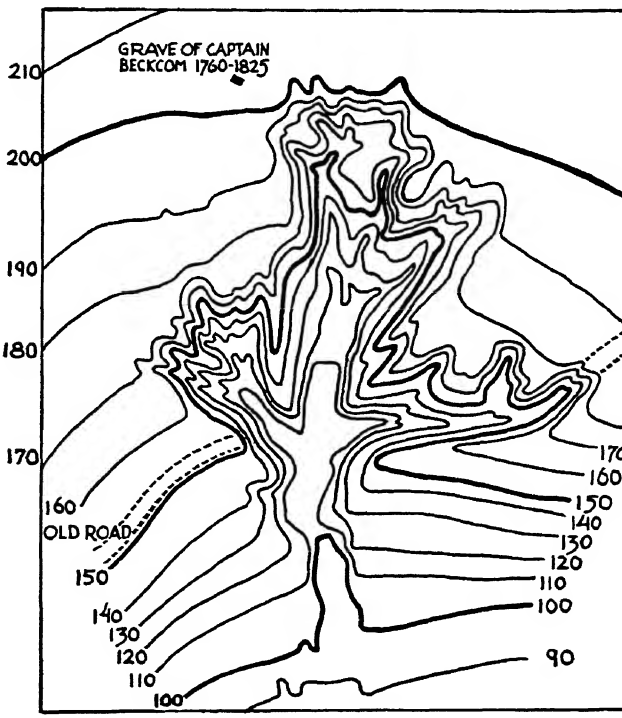


FIG. 36*b*.

Lengthening of the gully had already cut across the old road, in 1846. By 1937, it had increased its length 400 feet and had developed five times as many tributary gullies. Does this increase in number of tributaries partly explain why it had not become deeper at and below the old road trace? It is planned to move the grave of the Revolutionary War captain shortly. (Modified from Ireland, Soil Conservation Service. Published in *Journal of Geology*, University of Chicago Press.)

descending gradient which becomes less and less steep farther downstream. Every tributary valley joins its main at the same level, is the same depth as the main at the junction. And in this tree-like pattern the bedrock has no fractures, even closed ones, along the stream courses. Furthermore, there *are* earthquake

fractures (faults) known in this plateau country, none of them open cracks like these canyons.

The idea to which we devoted the above discussion was once a popular explanation of river valleys, still is to be heard among uncritical visitors at the Grand Canyon. It can be entertained only by minds sparsely provided with significant facts on the question and unaware that only by accumulating facts, more facts, and ever more facts can we correctly explain anything.

Again, let's look at the abandoned plowed field and forecast its future. Will all these hundreds of rivulet courses in time become ravines? There isn't room enough. Some of the favored ones, in deepening and widening, will destroy closely

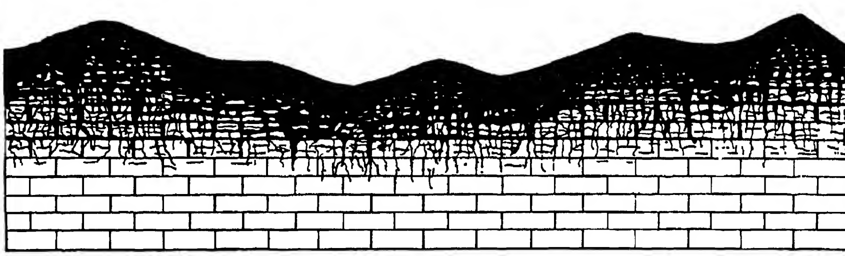


FIG. 37. Normal Relation of Mantle Rock to Bedrock. (Illinois Geological Survey.)

adjacent ones and perhaps eventually only one or two ravines will survive, their slopes then carrying off the rainfall that originally fed the hundreds of tiny separate rivulets.

Development of a drainage system in nature seldom follows the scheme outlined. Rarely is there a complete and prompt destruction of a vegetative cover. Rarely is a deep soil fully formed before running water gets to work. The plowed field simply illustrates what most every one has seen occur in some form: the removal of soil by rainwash, the concentration of the running water, and the formation of infant valleys. Beneath the soil everywhere is consolidated bedrock, down into which the larger streams erode their deeper valleys. Why isn't the land surface all consolidated rock? Why is there a soil almost everywhere on top of it?

MANTLE ROCK. The geologist has what he thinks is a better term for this unconsolidated material. He calls it "mantle rock." It is solid (not liquid, not gas); hence it is rock, the stuff of the lithosphere. Walk across the plowed field. Dust or mud (tiny particles of rock) will smear your shoes in consequence. Below plow depth, in the digging of a well, let's say, the mantle rock has no dark organic matter. We have penetrated into the subsoil. Still deeper, it has more stones in it, larger stones, too, until the well finally reaches bedrock itself. There is a gradation, therefore, between mantle rock and bedrock. Apparently, both were once one and the same kind of material. Either bedrock has been changed at the surface to mantle rock, or mantle rock material has been altered at sufficient depth to become bedrock.*

Which is the correct answer? Consider these facts.

1. Regions of very steep slopes commonly have no mantle rock. Bedrock "crops out" in ledges and cliffs.
2. Water freezing in pipes, bottles, or automobile radiators bursts them.

3a. All the different kinds of rocks of the lithosphere, together, average about 5 per cent iron in composition. Not metallic iron, of course, but iron in chemical combination with numerous other elements.

3b. In mantle rock, the iron is almost universally combined with oxygen; whence the common rusty yellow or brown or red colors.

3c. Chemically, oxygen is the most "active" constituent of the atmosphere.

If you don't yet have the answer, go over the question and these items again before you read further.

Here is a broad flattish land area with a thin mantle rock cover, almost too thin to cultivate. The bedrock is common granite, composed of small interlocking crystals of three or four

* Even where, for special reasons, the above gradation does not occur, there is this same relative position of mantle rock above consolidated bedrock.

kinds of minerals. It has cooled, and crystallized, to its present condition from a once molten mass a mile or so beneath the surface. Like most rock composing the lithosphere, it has numerous deep, closed cracks in it. The cracks are not so tight but that they leak when it rains, and water runs down into the rock. In dry weather, air replaces the water. Both bring oxygen and carbon dioxide. Thus the three most active constituents of the atmosphere penetrate into the rock.* A quarry allows us to go down fifty feet below the surface of the area. The cracks or "joints" obviously go deeper than this; you can trace them down the quarry sides and across the bottom. The rock is rusty colored along them, less and less so with increasing depth. And crumbly, for a little hammering separates and breaks the crystals. Alongside the quarry is a big pile of rejected rock, no good for monuments. It was discarded when the quarry work started; it is the surface part of the rock. It is rust-stained. When hammered, it also is somewhat crumbly and, though it may look strong and durable, the large pieces break readily under sledge-hammer blows. When it was quarried it broke up into smaller pieces than did the deeper rock, for it already had more and larger cracks in it.

Closer scrutiny shows that the colored crystals of the usable rock are bright and glistening, and harder than the point of your knife, while in the rejected rock they are dull and opaque and softer than steel. The granite is disintegrating into a mantle rock, where air and percolating water and frost have reached it. The change, aptly termed *"weathering,"* is complex, some of it simply making little pieces out of big ones (physical), some of it altering the very composition (chemical), all of it slowly destroying the bedrock, just as inscriptions on old monuments become illegible after a few centuries, and the blocks themselves crumble and break.

Mantle rock ("soil" is only the upper part of it) is the cumulative product of long, long exposure of originally consolidated rock. Organisms play a part in its making. Growing

* Chemical action on the rock follows, of course—oxidation, hydration, carbonation.

root tips are chemically active. Tree roots enlarging in a crevice may act as wedges. Burrowing animals open passage ways in mantle rock for air and water, bring detritus to the surface, aid greatly in the later stages of weathering.* All in all, the consolidated granite rock of the quarry is slowly evolving to a different material. In the deep-seated environment where it was made, it was physically and chemically adjusted. It would have remained granite to the end of time. But it became transferred to a new environment, the surface environment (air-water-frost-organisms), and here it proved to be unstable, unadjusted. The change to mantle rock expresses the response of rock material to new conditions, literally an adaptation to environment. As mantle rock, it will never change to anything else while it remains on the surface where it was formed.

STREAM LOAD. The mantle rock of the plowed field, though physically and chemically stable, was precariously situated on a slope, not permanently placed. Eventual removal is inevitable.† In rain and in wind, as mud or as dust, it leaves its birthplace and almost always travels downgrade. Stream load comes very largely from loose mantle rock. Where streams cut into consolidated bedrock they do so with tools provided in the first place by weathering. The "tools" come to the stream via slope wash and hillside rills.

The muddiness of the Missouri River is almost proverbial. "Too thick to navigate," said Mark Twain, "but too thin to cultivate." And almost all that mud was stolen from the soil of its drainage area; very little indeed came from actual grinding of pebbles on a rock-bottomed channel. The land surface between streams is lowered by such removal, the zone of atmos-

* The lowly earthworm outranks all other burrowing animals in his geological importance.

† If rainwash, winds, etc., constantly remove the mantle material, why is not most land bare rock? If mantle-making is more rapid than its removal (wasn't that your answer?), then why isn't mantle rock indefinitely thick? The earth is old enough, weathering has been going on for millions of years. The answer now required is a statement of ratios, and explains why steep slopes have thin mantles, gentle slopes have thick. "The thicker mantle rock becomes, the ...." You complete the statement.

pheric attack moves down, more bedrock becomes mantle rock, to be carried off in its turn during this long, slow series of changes. Weathering is essential to the loading of streams.

PERMANENT STREAMS. A drainage map shows small streams converging and joining to make large ones, yet everybody knows that in dry weather the small ones dwindle and disappear, while the large streams continue to flow. This is in part because the large ones do not get all drained out before the next rains come.* The small streams are temporary, the large ones are permanent.

LIFE HISTORY OF VALLEYS. Granted that streams have widened and lengthened and deepened their valleys to present sizes and proportions, one may ask how far such

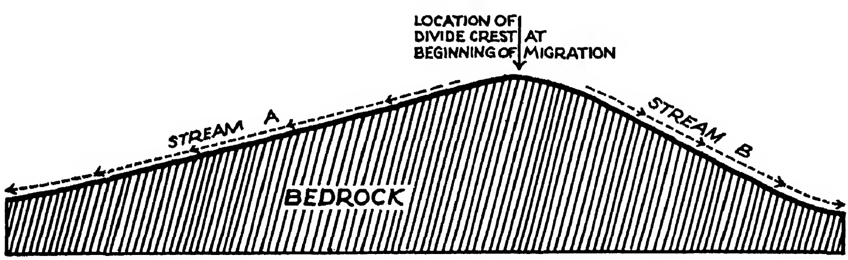


FIG. 38. Asymmetrical Divide, Providing Possibility of Migration.

changes can continue in the future. Gully lengthening upslope in the plowed field on the hillside could continue no farther than the top of the slope. Rain falling on the opposite side of the hill must run off the opposite way, down along a competing group of gullies. Headward lengthening of the two groups will narrow the divide top until its area no longer receives enough rain for adequate concentration, the prime requisite for gully formation (Fig. 38). As gully lengthening may extend upslope almost to the divide summit, so valley lengthening of major streams may occur back to major divides

* But there is a reserve supply of water for large streams during the drought. You locate the reservoir, remembering that the larger the stream the larger the valley, and that valley "largeness" includes width and depth and length. One of these dimensions is essential in solving the problem.

of the county, state, or continent, and no farther. After that, rainwash will simply feed the waste material, the mantle rock, into the headward portion of the stream and the divide will slowly become lower.

If, however, one side of the divide has softer rock, or a steeper slope, or more rainfall, its streams will carry off more of the summit waste and the divide crest will be shifted horizontally * as it is lowered. Yet at any stage in this sequence the lengthening valley cannot quite reach the divide crest.

Let's visualize a land surface, uplifted rather recently in geological time. Call it the Colorado Plateau (Fig. 39) or the

FIG. 39. Diagram of Colorado Plateau. (After Schuchert and Dunbar, *Outlines of Historical Geology,* Third edition, John Wiley and Sons.)

Sierra Nevada (Fig. 40). As soon as the uplift begins, running water starts its destructive work. But the land rises faster than weathering makes mantle rock, faster than the streams cut down into bedrock.† Finally the plateau- or mountain-making movements cease and erosion is free to work uninterruptedly. Slopes descending from the uplifted region to adjacent lower land are steep, and the streams must use them. They are im-

* Make a cross-section diagram to show three successive stages in this "migration." Assume that steepness of slope is the cause of divide shifting and start with the profile in Fig. 38.

† If rising were no faster than degradation, would a Colorado Plateau or a Sierra Nevada ever be formed?

petuous streams, tumbling repeatedly over rapids and falls as they descend. Velocities are as high as they ever will be, higher than they ever again will be. Pebbles, cobbles, even boulders, are rolled along their channels.* Bedrock is being worn away beneath them. Downcutting is a stream's first order of business. Shortly (ten thousand years, a hundred thousand) these gully ways and ravines become gorges and canyons, still carrying swift streams, still being deepened. There's scarcely room at the bottom for a railroad or a highway alongside the stream. The valley slopes may be cliffs of bare rock and, even if vegetation-covered, they are too steep for farming and their soil is

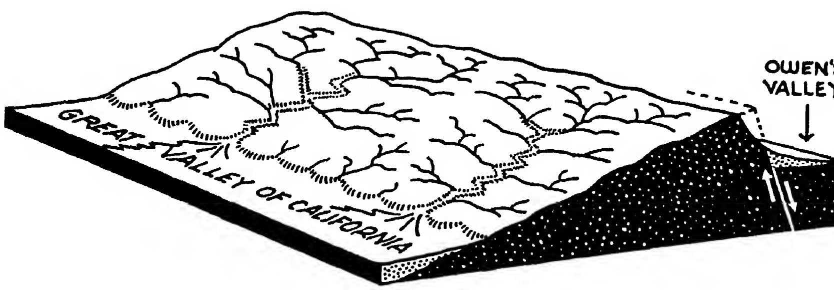


FIG. 40. Block Diagram of Sierra Nevada. (After Matthes, *Professional Paper* 160, U. S. Geological Survey, 1930.)

too thin and patchy. The cross sections of the young valleys look like huge capital V's.

Early in this valley deepening, approximately in its ravinehood, the upper zone of unsaturated rock is cut through and water-soaked rock is encountered. Seepages and springs then appear on the lower slopes. Discharge from the ground-water reservoir augments the direct runoff and the stream ceases to go dry in droughts.† From now on, it works twenty-four hours of every day in the year. There is much yet to be done; the stream valley is still far above its depth limit.

Downcutting or valley deepening, most rapid where the

* Those bumping and grinding sounds you think you near through the roaring of the water are real.

† You don't need this statement. You worked it out yourself, a page or so back.

stream is swiftest, will decrease downstream, out on the lower land beyond the plateau or mountain range, until where the stream enters the level sea all gradient has disappeared and deepening is impossible. Up in the highlands, this deepening is destroying the very conditions which made it possible. Like the ever-gentler slopes of a wasting divide, the stream gradient is becoming less and less, the work of down-cutting slower and slower. Theoretically, down-cutting should cease along a stream (entire length, or any one part) when the lowered gradient will just suffice to carry off the water and its load.*

Now let's look at the sides of the V-shaped valley. They are essentially hillsides, their outcropping rock is subject to weathering, their patches of mantle rock on gentler slopes are subject to rainwash and gullying. Isn't that why the cross section has sloping sides instead of being vertically walled, as narrow at the top as at the bottom? Slides of loose debris, slow creep of water-soaked soil, muddy storm-water rivulets; all bring weather-loosened waste down to the bottom. The stream there, like an endless conveyor belt, carries it away. If there were no simultaneous deepening, this wasting away of the valley slopes would reduce their steepness. But deepening there still is, and will be for many centuries to come.†

This widening, however, is *all* at the top. The valley bottom still remains hardly more than an angle between the two converging bluffs. You have seen river valleys with (Fig. 41) flat bottoms separating the bluffs; wide enough for farms, for villages, cities. Obviously, they were not made by this procedure. A different series of changes is necessary to widen valleys at the bottom. Consider the diminished velocity of a stream as downcutting decreases its gradient. Consider all the irregularities along a stream channel; variations in rock resistance, the presence of sand bars and gravel bars, undercut and fallen trees, driftwood accumulations. A weakened cur-

* Why does a turbid stream need a steeper gradient to give it the same velocity that a clear stream of the same size has?

† Another problem of ratios! When will a stream valley begin to develop a wider-at-the-top, more flaring $\vee$?

rent will tolerate them, will be deflected by them, will undercut the opposite bank where it is deflected and thereby have the channel course altered. Where the channel is so shifted that the stream also undercuts the valley wall, width at the bottom is increased. The newly made curves are not permanent; the channel must continue to suffer shifting. If we could photograph the channel course from an aeroplane once a

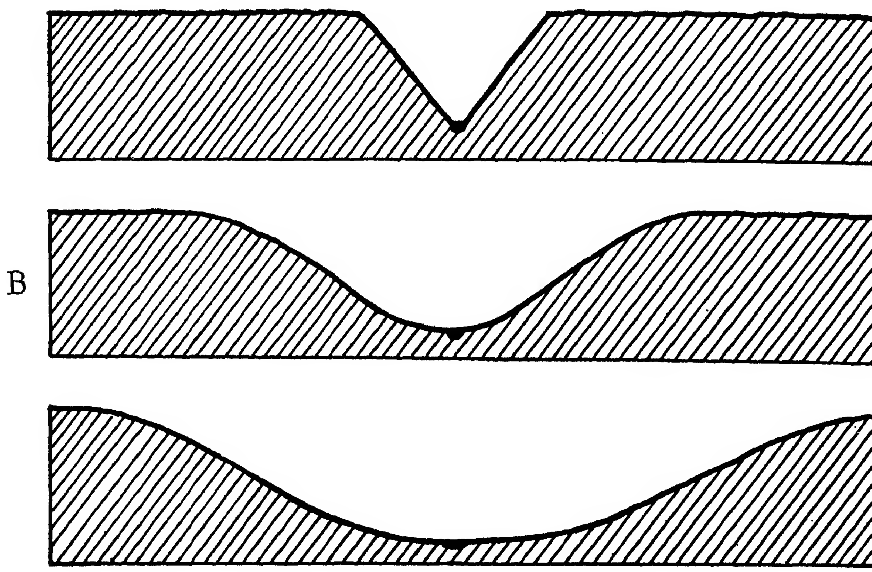


Fig. 41. Valley Cross Sections.

A. The very youthful, canyon-like valley with steep sides and no bottom width.
B. The more flaring V-shaped valley cross section. Initiation of bottom width.
C. Gentler slopes and an increase in bottom width finally destroy the resemblance to a capital V.

year for a thousand years and then combine the successive pictures to make a cinema reel, don't you think that channel would actually squirm? In hundreds of places the outside of the squirming course would undercut the valley bluffs during that thousand years, and thus valley bottom widening would be advanced. All the while the stream could be slowly deepening its valley, putting the finishing touches on that part of its task.

Valley flats, from a few hundred feet wide to a few miles across, are common. Those greater ones of the Nile, the Tigris, the Euphrates nurtured large populations at an early date and were a factor in the development of nations and cultures of the ancient world. The valleys of the Mississippi and of its larger tributaries are good examples, also. Such valleys are obviously farther along in their life history than are canyons. They are near, or have reached, their depth limit; their low-gradient streams swing leisurely in broad curves and loops;

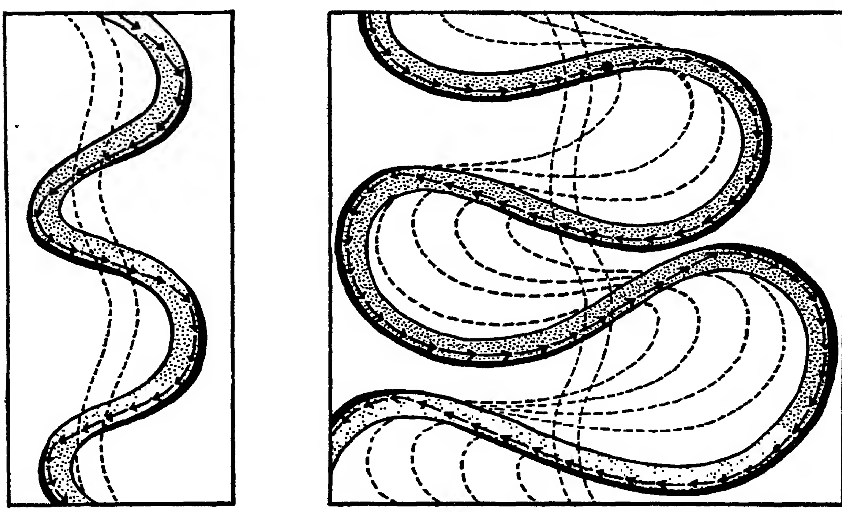


FIG. 42. Enlarging Meanders. (After Salisbury, *Physiography,* Third edition, revised, Henry Holt and Company, 1919.)

their bottom widening seems to have no future limit. They are no longer young; they are mature or old valleys.

The habit of swinging in great arcs or curves grows on a river, once it has started a valley flat. The current, thrown to the outside of the curve, erodes that bank; the slack water on the protected inside of the curve invites deposition of sand and gravel. Maintaining the same channel width, the curve grows larger. It is only one of a series of S curves (Fig. 42), all of which enlarge in the same way. The diagram shows what is inevitable here and there from time to time, and how this provides another mechanism for channel shifting, and its conse-

quences in lateral planation or valley widening (Fig. 43). Meanders, these enlarging loops are called, after the Meander

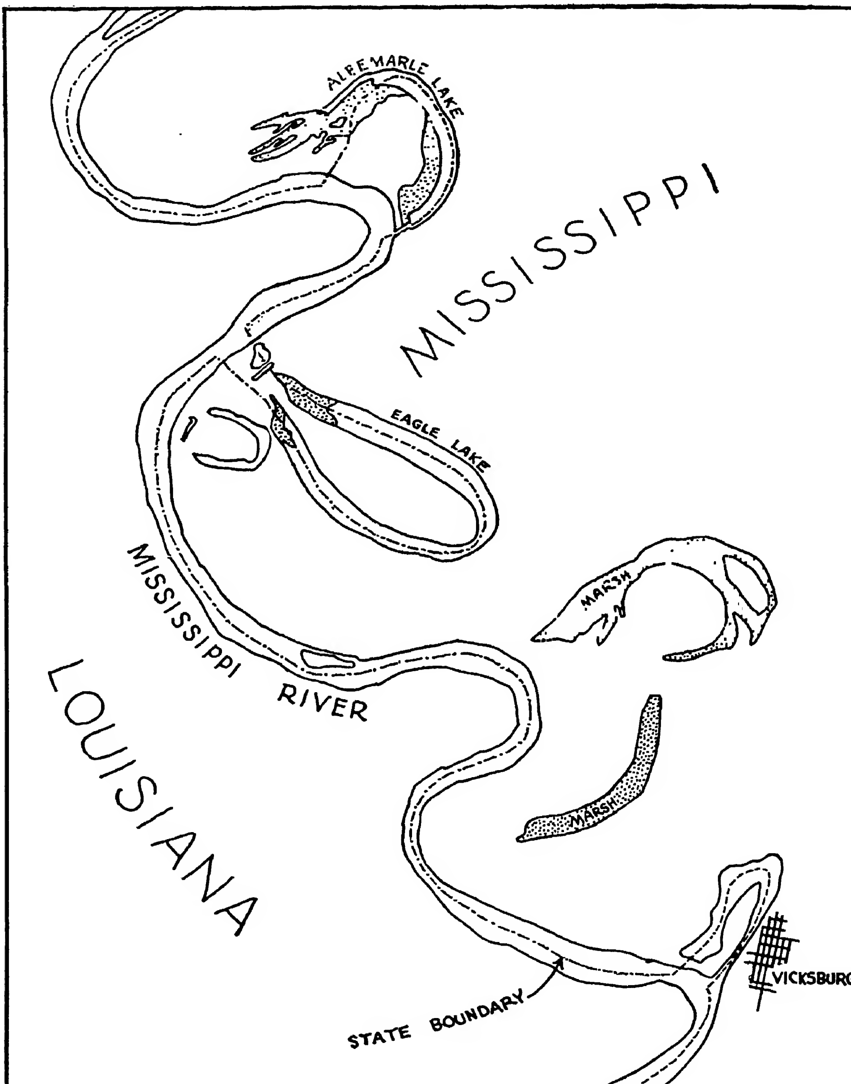


FIG. 43. Old Man River and the Louisiana-Mississippi Boundary Line.

River in Asia Minor whose course is strikingly of this pattern. A floodplain, we usually call the wide valley bottoms whose

stream in flood habitually rises over channel banks, spreads far and wide across the river-made lowland.

That uplifted land mass which we visualized as like the Colorado Plateau or the Sierra Nevada now has been rained and snowed on for hundreds of thousands of years. The main valleys have been cut thousands of feet deep in it, have been widened somewhat more tardily, though to many times their depths, and have been lengthened until only narrow divides separate opposite-flowing streams. Many more valleys have appeared as the main streams trenched the uplifted region, tributaries to the master streams, and subtributaries to the tributaries. All of them together now make a complete drainage system for the region's rain water and snow water. Seen from a stratosphere balloon, the plateau or the range looks something like the abandoned plowed field we earlier walked across. There is, however, a more important difference than that of magnitude. These river valleys have about reached their depth limit, and further changes by running water will be largely in valley widening and in wearing down the ridges between adjacent valleys. All valleys except the very twigs of the tree-like drainage system are mature, and the main valleys (where larger streams have been working for a longer time) are past maturity. Old age will come to all the valleys eventually, old age expressed in terms of a life work well along toward completion.

Erosional age of a region. In the early history of the new uplift, there are large areas without valleys of any kind, and what valleys do exist are youthful and canyon-like. The region as a whole is young. Later comes lengthening of the early valleys and budding out of tributaries, gradually reducing the area of broad, valleyless uplands. Finally the multiplication of young tributaries dissects the uplands into a fretwork of ridges and valleys. Meanwhile the early streams, the master streams, have been approaching their depth limit and have begun bottom widening of their valleys. By the time valley bottom flats appear in them, undissected uplands have nearly

vanished. Maturity of the master-stream valleys thus arrives at the time the region has lost its original slopes, has become that fretwork of divides and valleys. This is also maturity of the region as a whole.

But note that there are far more young valleys than mature ones in the mature region. Tributaries must always lag in their development; they don't get started with the master streams, and they have much less water with which to erode their valleys.

After the region has as many valleys as its rainfall and the character of its underlying rock will permit, further changes will be largely in valley widening and in slope wash. Widening of valleys means narrowing of divides. Since on divides themselves the only running water is slope wash and rills from their own rainfall, divide wasting and lowering will lag much behind development of the valley system. Very slowly, and ever more slowly as old age creeps on, slope wash will make gentler hillsides and lower hilltops. Erosion will stop only when gradients are so low, velocities therefore so slight, that mud and sand can no longer be carried away. Such an actual end to *all* erosion probably never occurs, but it may be approximated.

The lofty plateau or mountain range has now vanished. The rock of which it was composed, changed into soil, then removed by rainwash and streams, now exists as mud and sand below ocean level at the river mouths. A lowland plain lies where once the highland stood. The work of running water is essentially complete. Regional old age has come. The cycle of stream erosion has been run.

No cycle of erosion has ever been witnessed! Surviving temples, monuments, abandoned irrigation works, and city sites of early human cultures along the Nile, Tigris, and Euphrates show how little change in these great river valleys has occurred in the last four or five thousand years. The concept of the cycle is built on (1) the known work done by streams of today and (2) the conviction that most river valleys are the cumulative result of the work of their streams. The cycle demands time far beyond the span of human history. Like so

many concepts that we accept, it is an interpretation, not an observed fact. Perhaps you noted that we asked nothing of wind or waves or glacial ice or ground water in eroding the original highland, that we never once thought of volcanic action or earthquake movements occurring while the streams were slowly advancing toward their goal. Was that result, the *"base-leveling"* of the region, inevitable? Would wind, waves, glaciers, ground water aid or retard the result? Would volcanic action assist or interrupt? Would earthquakes help, or would they interfere or prevent? More hooks to hang up until we find an answer we can defend with adequate facts!

BIBLIOGRAPHY

AGAR, W. M., FLINT, R. F., and LONGWELL, C. R., *Geology from Original Sources,* Chapter III, Henry Holt and Company, New York, 1929.

ALLEN, V. T., *This Earth of Ours,* Chapter III, Bruce Publishing Company, Milwaukee, 1939.

CRONEIS, C., and KRUMBEIN, W. C., *Down to Earth,* Chapters 7 and 8, University of Chicago Press, 1936.

HOBBS, W. H., *Earth Features and Their Meaning,* Chapters XII and XIII, The Macmillan Company, New York, 1931.

LOBECK, A. K., *Geomorphology,* Chapters III, V and VI, McGraw-Hill Book Co., Inc., New York, 1939.

LONGWELL, C. R., KNOPF, A., and FLINT, R. F., *Textbook of Geology,* John Wiley and Sons, New York, 1939, Second Edition. Part 1, *Physical Geology,* Chapters 2, 3, and 4.

LOOMIS, F. B., *Physiography of the United States,* pp. 41-50, Doubleday, Doran and Company, Garden City, 1937.

CHAPTER VI

EFFECTS OF UNEQUAL HARDNESS OF ROCKS ON STREAMS

While working out this concept of the cycle of erosion, we forgot also that the plateau or mountain range may be made of diverse kinds of rocks, that under the same climate some rocks weather more rapidly than others, that beneath the same stream some wear away more rapidly than others. Both divides and valleys may show interesting features due to this variable factor, unequal yielding of different underlying rocks to the attack of erosion.

One of the most common rock structures is stratification, or layering. Stratified rock is almost invariably consolidated sediment, and commonly it records an ancient overlap of ocean water on a part of the continent, now become land because of later diastrophic uplift, i.e., uplift by movements in the subjacent rock. The layers are successive additions of mud and sand to the bottom, like the layers forming today in all oceans. Cementation* has made firm, indurated rock of the originally unconsolidated sediment. If the uplift which caused withdrawal of the sea was uniform, the strata may be nearly horizontal, as when first deposited. They may, however, have been bent, even folded and faulted, by the movement and so may now lie at all possible angles to a horizontal plane. Plains and plateaus underlain by stratified rocks are likely to have horizontal strata, mountains are likely to show tilted and deformed stratified rocks. Let's consider regions of horizontal stratification, with reference first to valley features, then to

* The cement is any mineral matter that ground water may deposit in the open spaces among the sand grains.

divide feature forms. There's nothing to say, however, unless the layers vary in resistance to erosion.

UNEQUAL HARDNESS IN HORIZONTAL STRATA. Most stratified rock still lies in flat or nearly flat layers, the position the sediment took when it was originally deposited. Stream sculpture of such rock produces some readily recognized land forms, such as rock terraces, buttes, and mesas. Reciprocally,

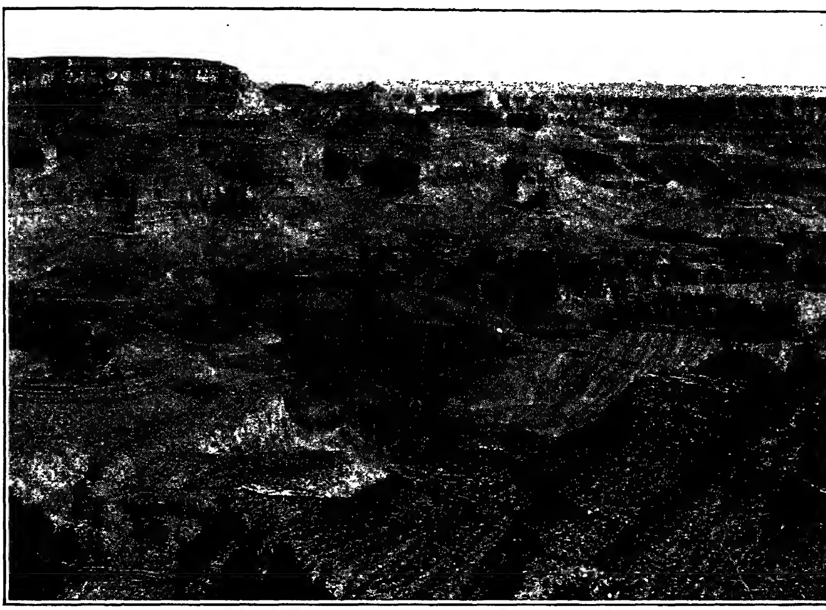


FIG. 44. The Grand Canyon of the Colorado.

The complexity of the canyon wall is due to the maze of short tributary canyons. The undissected plateau top shows in the distance. (National Park Service, Photograph.)

such rock may produce certain features of the stream gradient, such as rapids and waterfalls.

Rock terraces. Almost any picture of the Grand Canyon of the Colorado will show that it is not a simple deep cleft (Fig. 44). Instead, its walls are made up of a succession of gigantic rude steps leading down a mile below the plateau top to the river. Cliffs (risers) alternate with broad benches

(treads) of much gentler slope (Fig. 45). These steps are duplicated on the opposite side of the river, i.e., they are paired across the canyon. They also coincide with the outcropping

FIG. 45. Contour Map of Part of the Grand Canyon.

A portion of the plateau shows in the lower left. The star-shaped hill rises to the same level and has become separated by the headward erosion of two tributary gorges. It is a mile vertically down to the river (upper edge of map). Look at Fig. 115 to see why this map must have such a heavy massing of contour lines in places.

edges of the stratified formations of the plateau. These edges are clearly responsible for the step-like character. It is easy to see that the cliffs or risers must be edges of the more resistant formations. So the softer rock outcrops must be in that gentle slope between cliff base and tread or bench top, as shown in Fig. 46. These are rock terraces.* Arizona's aridity is in part responsible for their sharpness of outline in the Grand Canyon.

Waterfalls. A youthful stream with high gradient flows seaward in a valley cut into a plateau of stratified rock, hard and soft formations alternating. The rocks are horizontal, the stream descends. Thus the water crosses edges of the different formations on a long diagonal to the horizon. Make a cross-section diagram, if this is not clear. Any layer of weaker rock

FIG. 46. Diagrammatic Cross Section of the Grand Canyon.

cropping out in the stream bed will be more easily eroded than the overlying more resistant formation farther upstream, and the stream will cascade or fall over the edge of the upper hard layer to the deeper valley in the soft rock just downstream. At the falls itself, the stream will attack the edges of both formations. Here the weaker rock will yield more rapidly until a Niagara Falls "Cave of the Winds" will be formed back of the sheet of falling water (Fig. 47). Is it perfectly safe to stand under that projecting ledge of harder rock, the brink of the

* Why are the cliffs successively farther apart toward the top of the canyon wall? The upper hard formations are about as thick and as resistant as the lower, so the answer does not lie in that direction. Suppose you sketch a cross section of a very early stage of the Grand Canyon, cut down only through formation 7. How wide should you make it, compared with the width at that level in Fig. 46? Now deepen it through 6, and then through 5. What else must be happening during this deepening? .... Isn't that the answer?

† Why?

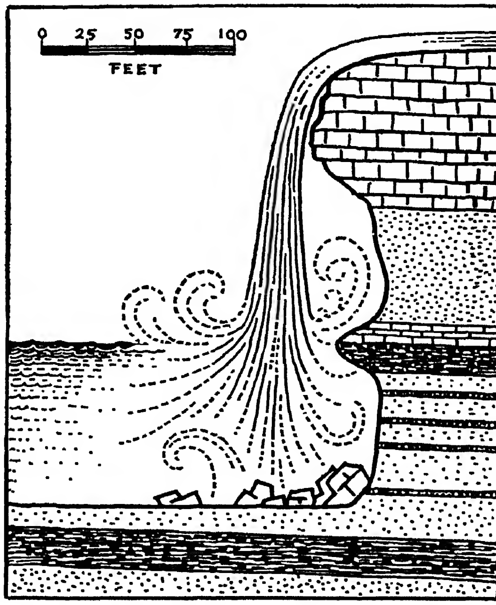


FIG. 47. Niagara Falls in Cross Section.

The plunge pool beneath the falls is as deep in places as the falls are high. (After Spencer, *The Falls of Niagara,* Canada Geological Survey.)

FIG. 48. Fallen Blocks at the Foot of Niagara Next to Goat Island.

falls? Will an accurate survey made twenty years ago show the brink precisely as it is today? Examine Fig. 48 for your answer.

Niagara is the best-known example of this type of waterfall. The river has almost no valley on the top of the low plateau. A narrow, steep-walled gorge begins just below the falls and

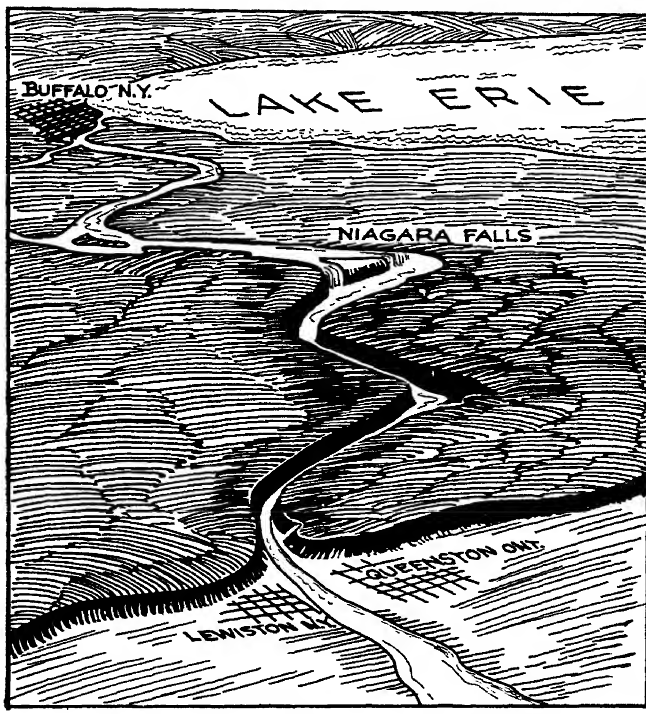


FIG. 49. Niagara Falls and Its Surroundings.

The northfacing cliff or escarpment. The gorge extends from the falls to Lewiston, N. Y., and Queenston, Ontario. Lake Erie and Buffalo, N. Y., in the distance. (After G. K. Gilbert, "Rate of Recession of Niagara Falls," *Bull. 306*, U. S. Geological Survey, 1907.)

leads to the lowland beyond the edge of the plateau (Fig. 49). Niagara has had several surveys since Father Hennepin first saw and sketched it. In each, changes in location of the brink are obvious (Fig. 50). In each, that brink has moved farther upstream. The average recession shown by these measurements through more than one hundred and fifty years

has been about four and a half feet a year. On the assumption that this rate will continue, the dashed lines of Fig. 50 show where the falls will be at intervals up to the year 2100.*

There are no Niagaras on the Colorado River through its canyoned course hundreds of miles long. Yet the river is

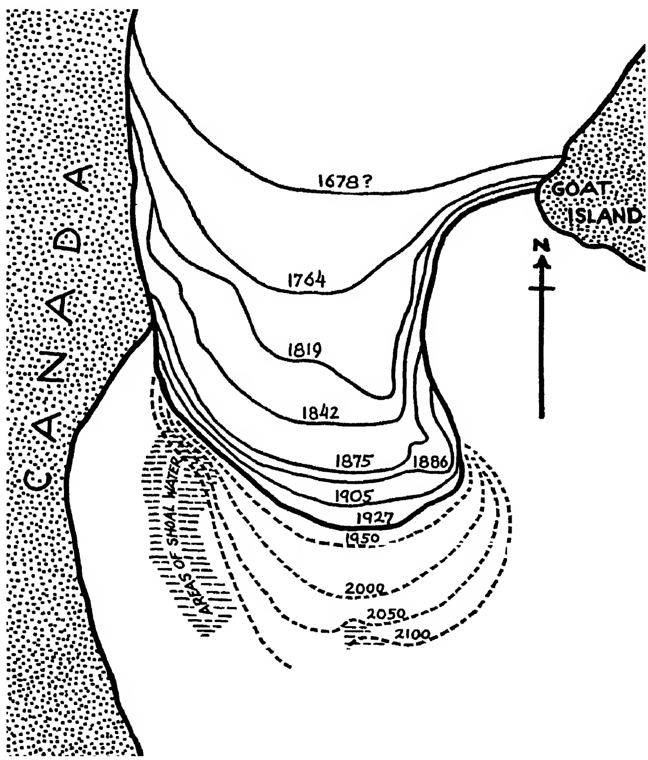


FIG. 50. Niagara's Crest Line: Past, Present, and Future.

cutting in a great series of alternating hard and soft, nearly horizontal stratified rocks. When Powell first proposed his historic boat trip down the unexplored canyon, from Wyoming to Arizona, he was challenged by some pessimist. "Nobody knows how many Niagaras there are along that canyon. You

* Now, you tell specifically *how* the gorge below the falls was formed. Precisely where did the falls begin? What information do you need in order to know how long the falls have existed?

can never get your boats over or around them." "Have you ever seen the Colorado?" Powell answered. "It's the dirtiest river on earth." * He was right; the great quantities or silt sand, gravel, and boulders carried and rolled along by the Colorado have enabled this vigorous young stream to saw down through hard layers in its bed about as rapidly as the softer rocks have been eroded. Rapids he found aplenty, but all were negotiable, and the only casualties in his party were the three

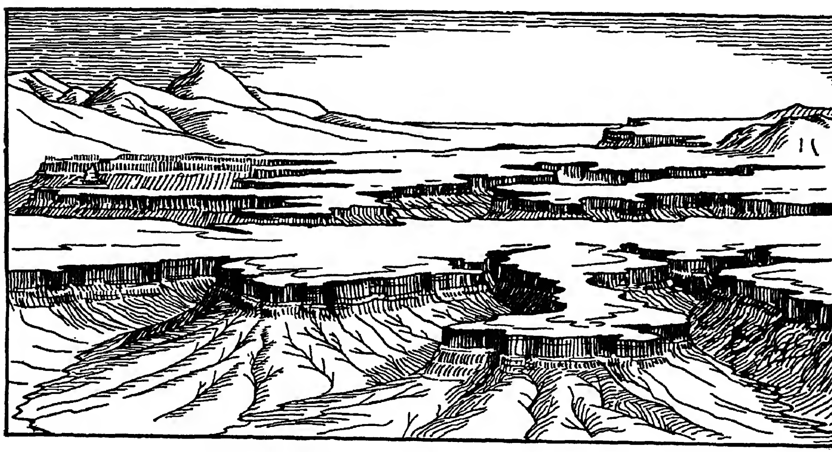


FIG. 51. Part of the Mesa Verde of Colorado. (After Salisbury and Atwood, "The Interpretation of Topographic Maps," Professional Paper 60, U. S. Geological Survey, 1908.)

deserters who climbed the canyon wall and were slain by the Ute Indians.

Obviously not all waterfalls recede upstream. Unless there is exposed in the stream bed a resistant layer lying approximately horizontally above a weak one, a waterfall will live its whole life in the place of its birth. Valley deepening destroys waterfalls. The resultant decrease in gradient destroys the chance that more might develop at lower levels as the valley is cut deeper. Only youthful streams can afford them.

Mesas and buttes. Let's climb up out of the valley now, and back on the surface of the plateau. It is a divide area, an

* Niagara's water is clear. Look to Lake Erie for the reason.

interfluve (Latin, between rivers), yet has suffered from the work of running water. Some minor gullies and ravines, dry except immediately after rains, mark temporary stream courses.

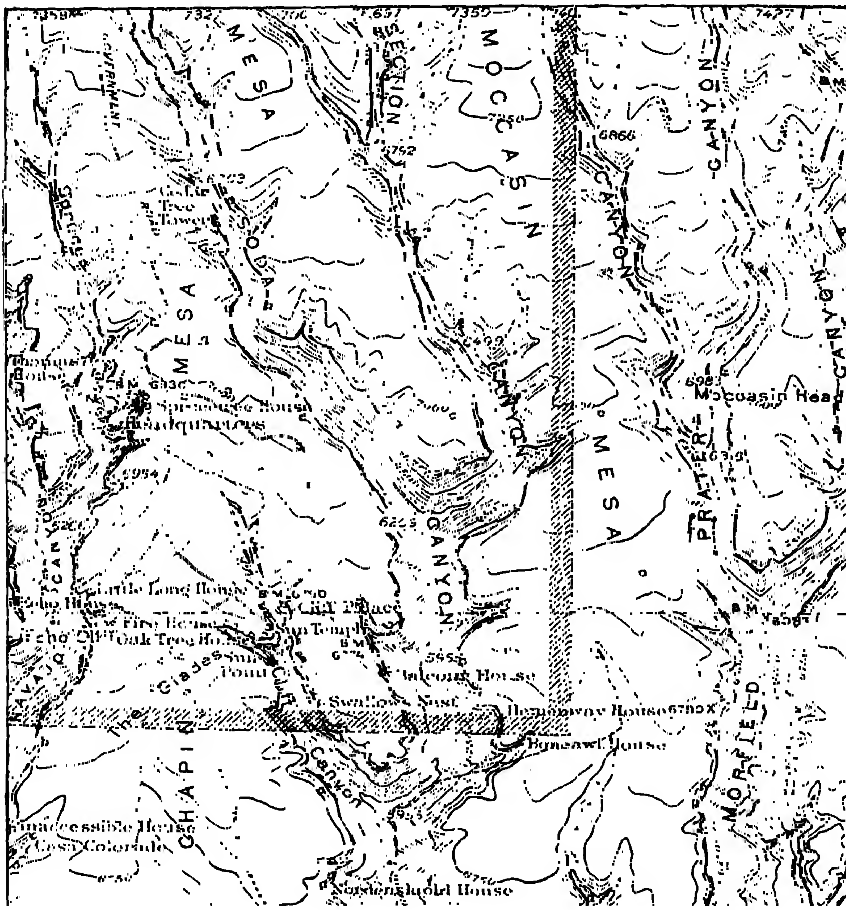


Fig. 52. Contour Map of Part of the Mesa Verde (contour interval 50 feet).

The "houses" are cliff-dweller sites. How far up did the Indians living in Balcony House have to climb with water from the canyon bottom? In approximately what direction is the observer looking in Fig. 51? (Soda Canyon Quadrangle, Colorado. U. S. Geological Survey.)

Everywhere else, unconcentrated slope wash alone has occurred. To the summit, climbing this last cliff! The top isn't a narrow ridge crest; it is broad and flat, a table land, a mesa. And

ahead, on the far side, the country drops off toward the next river valley with slopes like those we climbed. Though far from any permanent stream, this mesa is cliffed all around. It is a little plateau in its own right (Figs. 51 and 52). It would be easy to defend against a cavalry charge or an attack by tanks. The flat summit and the margining cliffs are the top and edges of a horizontal stratum of resistant rock. Once continuous over the entire region, it now lingers only in mesa remnants on the divides. Weathering of a weaker stratum beneath undermines

Fig. 53. Badlands of White River, South Dakota.

Not a relief model but the land surface itself, as seen from the Explorer II at an altitude of more than 13 miles. (After National Geographic Stratosphere Series II.)

the hard rock outcrop, thus making the cliff and its talus, i.e., the pile of detritus at the foot of the cliff. It is like the rock terraces in the Grand Canyon! Slope wash removes the detritus after further disintegration. The cliff is retreating on all fronts, the mesa is growing smaller. Here and there are portions of the mesa, already isolated by irregular cliff retreat. The term *butte* properly belongs to them.

Badlands. Think of two regions in maturity, with all the water courses developed that they will ever have. Both have the

same amount of rainfall, both stand at the same altitude above sea level, and both are the same distance from the sea. Will each have the same number of valleys in, say, a hundred square miles? Read that again.

Suppose the rock under this one is shale, a consolidated clay. Under the other is sandstone. Shale is softer than sandstone. It is far less porous, and it weathers to clay again. Won't there be more runoff here than on the sandstone, won't the debris be more easily removed, won't there be more tiny tributary valleys (the tributary-to-tributary-to-tributary-to-main-stream kind)? We say that such a region has a "fine-textured" topography (Fig. 53).

Now if the shale region is semi-arid to arid * and has had therefore no protecting mantle of grass or forest, and if its main streams have cut fairly deep valleys (so that the tributaries and the tributaries-to-tributaries, etc., have good gradients), that extreme of dissection known as *badlands* is produced in maturity. For grazing, for farming, and for getting across, they are all their name implies.

UNEQUAL HARDNESS IN TILTED STRATA. In almost no region of folded stratified rocks does the land surface parallel the stratification. Instead, the different underlying formations come to the surface more or less edgewise, and parallel, like the cord layers showing on a badly worn tire tread. And for the same reason: the wearing away of the more exposed outer part. Original upfolds of the deformation are attacked just as soon as the uplifting begins and, the greater the uplift, the more vigorous the erosional attack.† The first runoff will be exactly what you expect, down the steepest slopes of every square mile, a direct consequence of that slope.

Parallel ridges and valleys. But running water on that initial surface will soon discover that beneath it are rocks of varying degrees of resistance. Deeper erosion will occur along the belts of weaker rock and there the streams will gradually

* Where, when it does rain, it rains torrents.

† Because ....?

become shifted, abandoning the handicapped crossings of harder rock. Much of this shifting will be by migration of divides (pp. 92-93) and the stealing thereby of drainage areas by the more favorably located streams. Edges of hard rock layers will be left in relief, will come to constitute ridges of perhaps mountainous proportions lying parallel to the valleys and separating them. Yet here and there some of the earlier hard rock courses will survive, for streams must get out of the folded region to reach the sea. They will constitute deep notches across the mountain ridges, called *water gaps* or *narrows* * (Figs. 54 and 55).

Trellis drainage. All the details shown on the relief map of Pennsylvania, Fig. 56, are the work of running water. Most of the state is underlain by a great series of stratified rocks, the different members varying in degree of resistance to erosion. These rocks have been lifted from below sea level where they were formed; hilltops and mountain tops now are as much as three thousand feet above the sea. In part of the state this uplift was a simple vertical movement and the formations are still nearly horizontal. In another part, there was deformation by folding. Ignoring the southeastern part of the state where the relief is low, draw a line to separate the folded area (eroded mountains) † from the unfolded (eroded plateau). Now compare with the drainage map of Pennsylvania, Fig. 57. If you had an automobile road map, it would do almost as well, for main roads commonly follow the river valleys and use the water gaps, seldom climb over the ridges. The dendritic (*dendron,* Greek for tree) pattern of drainage lines in the northwestern half of Pennsylvania is in striking contrast with the trellis drainage of that diagonal central belt. The stems of the trellis are the hard rock crossings that have survived from an earlier pattern. They include the water gaps. But many times

* The water-gap part of a valley has high walls, is narrow and steep-sided, more V-shaped in cross section than the valley both upstream and downstream. Therefore the water-gap part of the valley is younger! Hasn't the stream been flowing here as long? It has, assuredly. What do we mean, then, in saying that the river valley is older both upstream and downstream from the gap?

† Remember what these mountains are. They are not upfolds themselves.

Fig. 54. Narrows or Water Gap of Delaware River across Kittatinny Range, Appalachian Mountains.

Looking north (upstream). The distant mountain is the edge of a tilted resistant formation. What explains its very even crest line? Softer rocks underlie the lower land in the nearer distance, with a broad floodplain along the river. (After Salisbury and Atwood, "The Interpretation of Topographic Maps," Professional Paper 60, U. S. Geological Survey, 1908.)

as many miles of the pattern's total of stream lengths lie along the belts of weaker rock.

In development of a drainage system on folded strata, the streams may discover weak rock along the axis of an upfold but

SCALE OF MILES

FIG. 55. Contour Map of the Delaware Narrows and the Lower Country to the South.

Contour interval is 20 ft. How deep is the Narrows where it crosses Kittatinny Range? Using a ruler and the scale of miles at bottom of map, how wide is the narrows (1) at bottom, (2) at top where the Range is crossed?

deep within it (Fig. 58). It is perhaps a little surprising to conclude, as we must if our reasoning is correct, that this will eventually determine a stream valley along the axial line of the upfold itself, where in the very first drainage of the uplift there stood a divide.

FIG. 56. Relief Map of Pennsylvania. (The Smithsonian Institution's Study of Natural Resources Applied to Pennsylvania's Resources, p. 7, Samuel S. Wyer, Consulting Engineer, Columbus, Ohio, Nov. 2, 1922.)

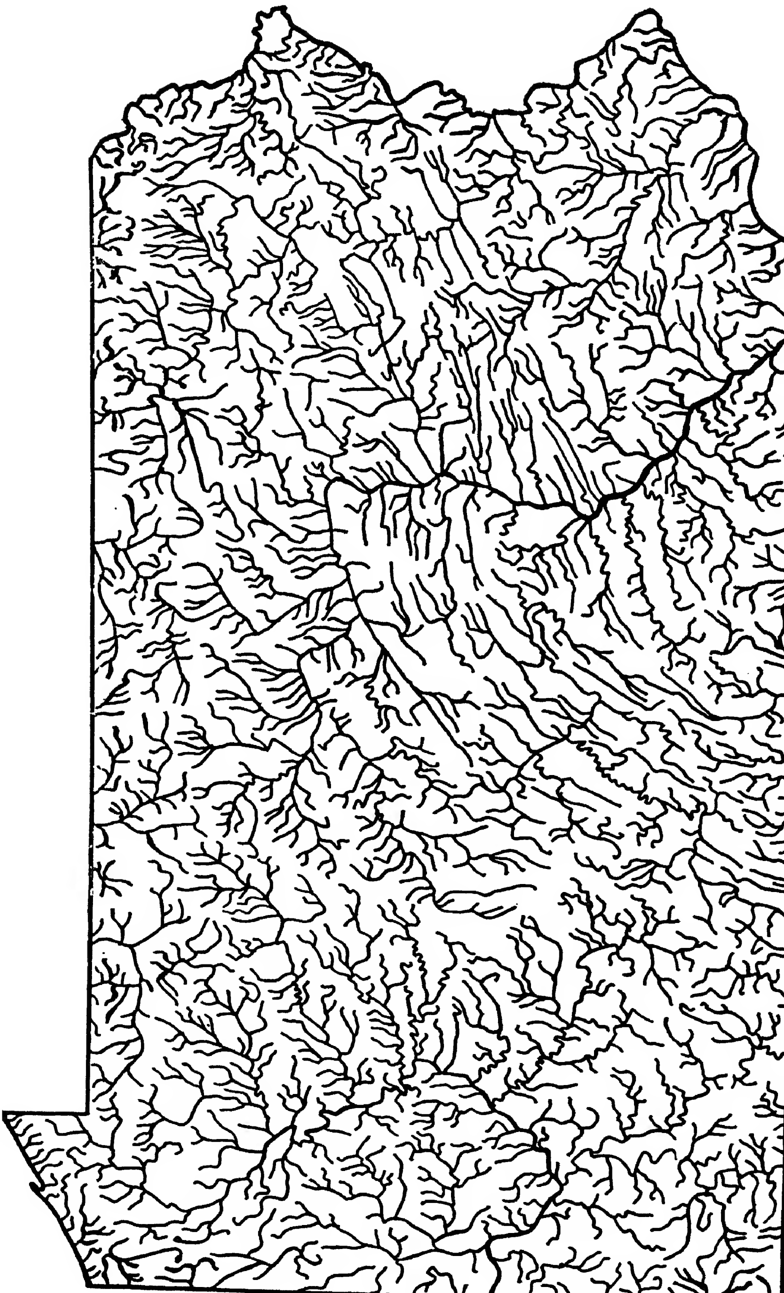


FIG. 57. Drainage Map of Pennsylvania. (After Wyer, The Smithsonian Institution's Study of Natural Resources Applied to Pennsylvania's Resources.)

The Appalachian Mountains of the eastern United States constitute a typical region of trellis drainage on folded rocks. Their folding and uplift occurred very long ago. The original mountains have vanished, the drainage pattern is maturely developed, running water has etched out more and smaller mountains along the grain of the original folding. Eventually the present mountains will be destroyed and a *peneplain,* a base-leveled lowland, of extreme old age will lie where they now stand.*

Hogbacks. In contrast with the Appalachians are many ranges of the Rocky Mountains. In the Rockies (1) uplift has been much more recent, (2) folding has been more open, and

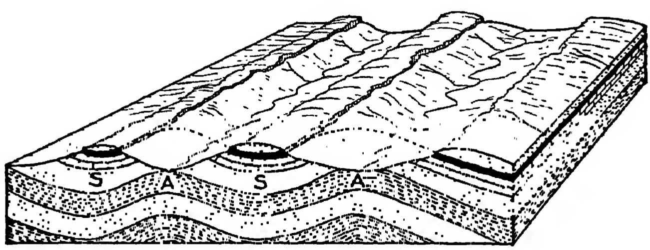


FIG. 58. Stream valleys along upfold axes (AA), with downfolds (SS) becoming divides. The black stratum, once continuous along the broken line, compares how in resistance to erosion with the thicker strata beneath it? (Longwell, Knopf and Flint, *Outlines of Physical Geology,* John Wiley and Sons, 1934.)

(3) erosion has uncovered a core of non-stratified, more resistant rocks (Pikes Peak granite, etc.) beneath the sediments (Fig. 59). Trellis drainage is much less in evidence than in the Appalachians and exists only on the lower flanks where the sedimentary rocks still remain. The ridges of harder strata here are called *hogbacks.* Generally, their gentle slope, which is with the tilt of the strata, dips away from the mountains; their steep slope, across the bedding, faces toward the central part of the range.†

ANTECEDENT STREAMS. There are many more controls on stream courses exercised by rock structure. We can't

* Will conditions then maintain a trellis drainage pattern?

† Under erosional attack, hogbacks migrate. Toward the range, or away from it?

consider them here; we know too little geology yet. One more case must suffice.

The Arkansas River in Colorado flows eastward toward the great Front Range of the Rocky Mountains and crosses it by way of the very youthful Royal Gorge. The South Platte River does the same thing by way of another canyon. The Laramie River similarly crosses the Laramie Range in Wyoming. The Bighorn River, also in Wyoming, does the same thing with another mountain range. The Columbia River, along the Oregon-Washington boundary, crosses the Cascade Range in the longest water gap on the continent, seventy miles

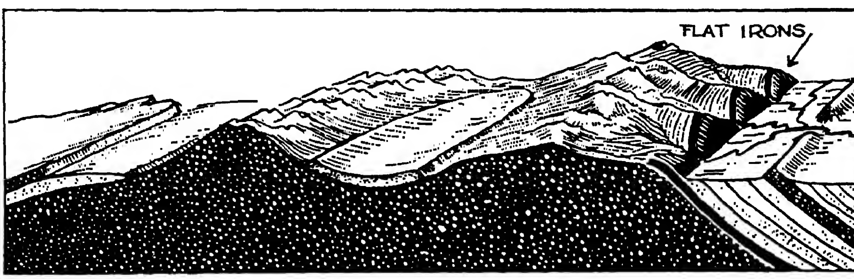


FIG. 59. Structure of the Southern Rocky Mountains.

The folded sedimentary rocks once completely covered the range. Edges of the harder strata determine hogbacks. An unusual form of hogback is the "flat iron," a row of which occurs along the east (right) flank of the Front Range. (After A. K. Lobeck, *Atlas of American Geology,* Columbia University, Geographical Press, 1932.)

from end to end. All of these mountains are (geologically) fairly recent uplifts and all of these rivers apparently were flowing here before the mountains were made. They are *antecedent streams.* They simply cut down as rapidly as the ranges went up. The gorge-like crossings are not restricted to hard rocks, for none of these ranges has yet had its softer rock dissected out, as has the Appalachian mountain system. Perhaps the Susquehanna once possessed a continuous gorge, from north to south, across the Pennsylvania Appalachians (east-central part of Fig. 56). If so, all that is left is a series of narrows through the half dozen hard rock ridges now athwart its course.

Rejuvenation. Some pages back we queried the effect of diastrophism on the orderly sequence of the erosion cycle. Let's now put our question in more definite form.

A main stream valley has advanced to maturity. Its gradient is low, for its depth limit has nearly been reached. Its bottom width is many times that of its widely meandering stream. Its walls are no more than gentle slopes. Offshore from its mouth, there is a narrow continental shelf sloping with the same gradient the valley has, beyond which the ocean bottom descends much more steeply. This last item is of no significance if the

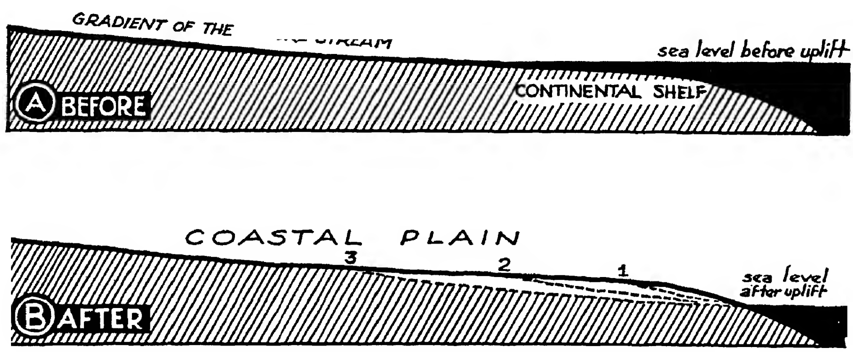


Fig. 60. Profile of Rejuvenated Stream Valley.

1, 2, and 3 are successive positions of the head of the younger valley; the dotted lines leading to the new coast line are successive gradients as the rejuvenated stream deepens as well as lengthens its new valley.

sea level remains the same, for it is sea-surface level, not sea-floor level, that determines depth limit back on the land.

But now a simple uplift of the region occurs, without folding or faulting, without even any tilting. The sea level becomes lowered with reference to the stream, twice as much (let's say) as the depth of water on the edge of the shelf. The shelf becomes added to the land and the stream becomes lengthened at its lower end.

In the last few miles of that newly added length is a considerably steeper gradient (Fig. 60). Descending it to the new sea level, the stream's velocity is increased and downcutting toward the new depth limit starts. The youngest portion of

any normal valley is at the upper end; here it is at the lower end. Anomalous, isn't it? What of the future, with this curious set-up?

The young portion lengthens as well as deepens, more rapidly than any normal valley head does because it has a full-grown stream pouring into it. Advancing upstream, this narrow young valley trenches into the broad floor of the mature valley already developed. The main stream has become *rejuvenated.* Its larger tributaries, those with flood plains, later share in this. Valley cross sections are as shown in Fig. 61, the upper mature or old valley recording the earlier and interrupted cycle, the narrow inner valley recording erosion since the rejuvenation, the starting of the new cycle. In some cases, the lengthening young valleys have *followed the meanders* of the old valley floor and thus have forced on them a crookedness

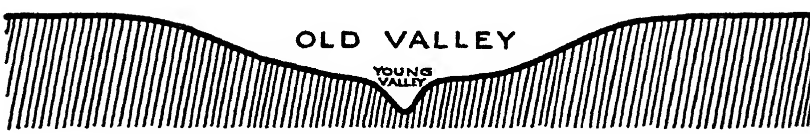


FIG. 61. Cross Section of Rejuvenated Stream Valley.

that few canyons possess. The whole record is transient, of course, for eventually the new depth limit will be approached and the inner valley will widen and destroy the broad terraced remnants of the old floor.*

Though there are many valleys carrying this record, not all young-inner-in-old-outer valleys have been made this way. A notable mistake was made by geologists studying the Grand Canyon, because they did not take account of another possible cause. The Colorado in northern Arizona has an inner gorge, far down in the canyon where the river has found granite, presumably much more resistant to erosion than the sedimentary rocks in the upper canyon walls. You see the alterna-

* Suppose that the uplift had brought the sea level down only to the edge of the continental shelf. Would rejuvenation have occurred? Suppose that the uplift only affected country back from the sea, but did not alter the location of the coast line. Would the streams have been rejuvenated?

tive at once? Curious that they didn't! But how to prove which explanation is correct!

The granite in the bottom of the canyon at Bright Angel Trail, where most visitors see the Grand Canyon, has been trenched about a thousand feet deep. Granite walls the lower fifth of the canyon's depth (Fig. 62). But traced both upstream and downstream, the contact of sedimentaries on granite comes down gradually to river level and in a few miles disappears, the canyon being walled entirely with the softer

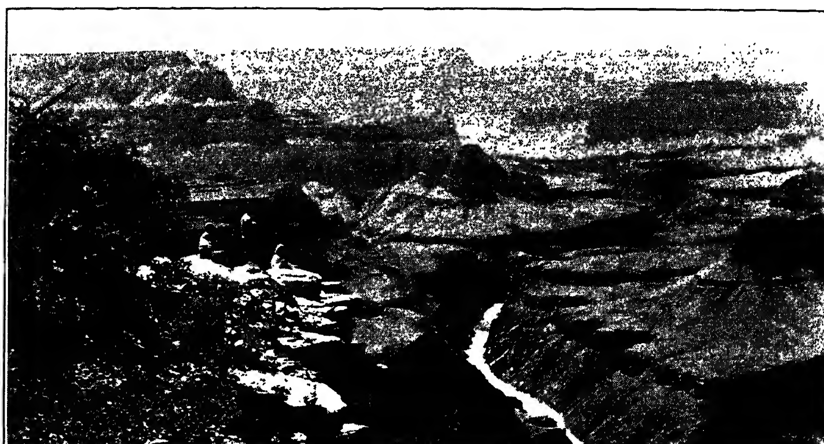


FIG. 62. The Narrow Inner Gorge of the Grand Canyon of the Colorado, Eroded in Granite beneath the Flat-Lying Sedimentary Rocks. (U. S. Department of Agriculture.)

sedimentary shales, sandstones, and limestones which determine its rock terraces. The inner gorge, though indubitably younger than the upper and much wider part of the canyon, is *not* a record of rejuvenation.*

Two cycles. Those remarkably long, narrow, nearly parallel ridges of the Appalachian Mountains possess another remarkable feature in common. Their crest lines are very even (Fig. 63). Peaks are almost lacking. Skyline drives and skyline trails involve insignificant grades compared with the

* You tell whether or not there is an inner gorge upstream and downstream from the granite.

climb up to them. The observer on the top sees, in all directions about him, ridge crest after ridge crest rising approximately to the level at which he stands. If the broad valleys on weaker rock between the ridges were filled up again, level with the existing crests, the mountainous region would become a plain at that summit altitude.

That would not be restoring any considerable fraction of the rock material which erosion has taken away. It emphatically would not be restoring the vanished original mountains. The folded strata would be truncated by that imaginary surface at the levels of the mountain ridge crests, just as much as they are truncated in the more rugged topography of the

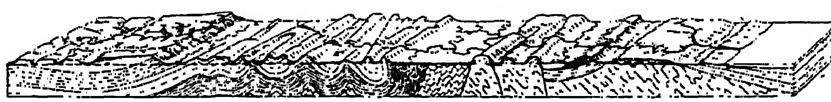


Fig. 63. Today's Remnants of the old peneplain across the Appalachian Mountain Summits. (Schuchert and Dunbar, "Outlines of Historical Geology," John Wiley and Sons, 1937.)

present. Our imaginary plain would have to be a plain produced by erosion.

For several decades, all geologists familiar with Appalachian topography have agreed that those even crest lines of the folded belt, extending from Pennsylvania to Alabama, do record a former lowland plain of erosion. Our imaginary plain once did exist. It was an ancient peneplain, the product of ages of weathering and stream work, of a full cycle of erosion. After the mountains were folded, the erosional attack continued almost to the end of the cycle. Even the harder formations were worn down by slope wash to low hills. But the mountain roots remained, the folded rock below the base level of the streams of that cycle.

Then followed a different kind of uplift, a very broad doming, the movement being wholly vertical.* The Appalachian peneplain was raised hundreds of feet, stream gradients were increased, streams rejuvenated, a new cycle started. But the

* Folding requires lateral, or horizontal, movement, doesn't it?

second cycle hasn't yet gone to extreme old age, else we would have no record remaining of the first. Weaker rocks have been dissected out, and the harder strata, left in relief, carry the record of the former peneplain in their even crest lines.*

* Most geologists think that there have been two such *partial* cycles since the summit peneplain was uplifted, and that streams today are just entering a third. That would require how many separate upward boosts of the region? Most of them think also that in the eastern part of the Appalachians, there are considerable areas (Great Smokies, southern Blue Ridge, Unakas) that never were peneplained in the first great cycle. What altitudes, relative to the even crest lines of the linear mountains, should such areas have? What about even crests of their own?

BIBLIOGRAPHY

Longwell, C. R., Knopf, A., and Flint, R. F., *Textbook of Geology*, John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology*, Chapter 5.

CHAPTER VII

DEPOSITION BY RUNNING WATER

There are two parts to a complete account of the changes brought by running water. We have sketched some of the leading features of the much larger part, the erosional work. Far less conspicuous, much less important topographically, and bulking a bit less in magnitude are the deposits made by running water. Where are the cubic miles upon cubic miles of rock waste resulting from the destruction of the first Appalachians? Easily answered if general terms will suffice; they lie in the Atlantic and the Gulf of Mexico, as stratified sediments deposited while the destruction on the land was occurring. Not much of the debris got very far out before it settled. Today's dredgings and corings of open ocean sediments prove that. No feature of oceanic circulation provides for the necessary repeated pickings-up and shiftings-forward of rock particles two and a half times as heavy as water. The debris undoubtedly lies on the top of the continental shelf of that time, or just beyond its far edge. Most of it isn't land today, so we will pass up the subject for the present.

Running water does, however, make deposits on the land. No sand grain carried or rolled along in a stream ever keeps up with the water that started it traveling. A local lower gradient, and therefore a slower current, may let the particle settle. A meander with lower velocity on the inside of the curve may cause deposition there. A temporary obstruction of driftwood may make a sand bar in its lee. Decrease from flood stage to the shrunken flow of a drought will bring plenty of the load to the bottom, to await the next high water. Flood water, out of channel, will deposit much of its load, for there is little velocity in the shallow inundations of valley bottom land. All these deposits are made in the stream water, but since

stream channels have their locations shifted in many ways the deposited material may be abandoned by its carrying agent for long periods before running water again finds it and begins to move it on again. Finally, of course, the sea is reached and the longest stop-over begins, in the delta at the river mouth.

ALLUVIAL FANS. High-gradient youthful mountain streams rarely escape directly to the sea. Lower, flatter land must be crossed almost everywhere. On it, stream velocities are decreased; thus demanding deposition. If the mountains rise sharply from the plains, the decrease in stream gradient is abrupt and deposition is localized at the junction of the two slopes. It occurs in the stream channel, it partially fills the channel. Water overflows, a new channel results while the old one is still carrying some discharge. Filling, overflowing (dividing), shifting; the stream develops a branchwork of changing *distributaries* * (Fig. 64) over its deposit and so builds up a fan-shaped deposit, acres to perhaps square miles in area, at the foot of the steep slope. The slope of the *alluvial fan* is the gradient of its distributaries. It is less than that of the eroding stream in the mountains and greater than the stream needs, after this deposition of its excess load, farther out on the plains.†

Small alluvial fans may occur any place where the same conditions exist: at the foot of minor bluffs, in plowed fields, in roadside gutters and ditches. But don't confuse them with deltas from which the standing water has been withdrawn.

ALLUVIAL FLATS. If the load contributed to a stream is greater than its flood-time ability to transport, excess material will be deposited along the length of the valley.‡ Instead of

* Tributaries might be called contributaries, by way of contrast.

† Suppose the stream is bringing a mixed load of large pebbles, small pebbles and sand grains out of its young valley to the head of the fan. Will the coarsest material be dropped at the head or out on the lower margin? Will the fan have the same gradient all the way across? If not, will it be steeper near the head, or near the lower edge? And what will happen to the fan when the supply of stream debris dwindles?

‡ Will the coarser, or the finer, be dropped first?

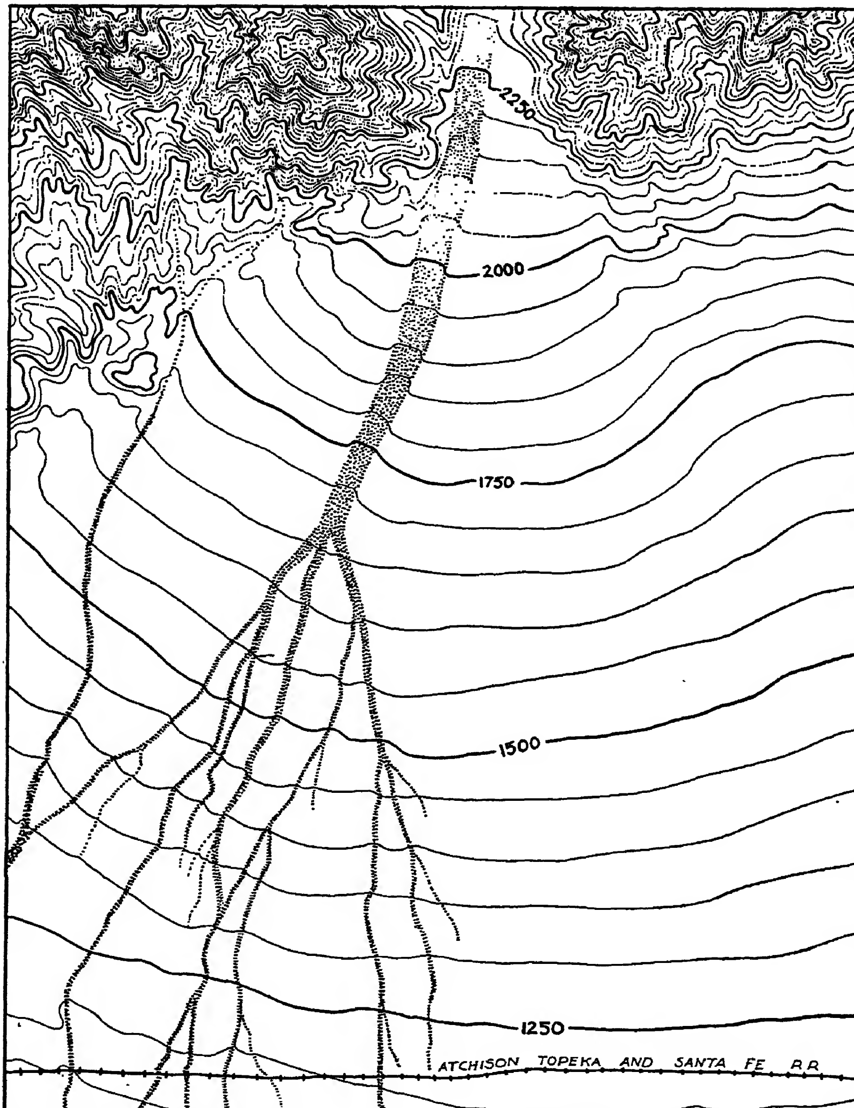


FIG. 64. Contour Map of an Alluvial Fan.

The mountains rise nearly half a mile in a distance of two miles back from the plain. Hundreds of temporary streams, minor tributaries to the canyon, flow on this very steep gradient and thus overload the main water course whose gradient is hardly 300 feet to the mile. The 1500-, 1750-, and 2000-foot contours bend out from the mountains, the 2250- and higher contours bend in toward the mountains. Where is the head of the fan? (After Salisbury and Atwood, "The Interpretation of Topographic Maps," Professional Paper 60, U. S. Geological Survey, 1906.)

being deepened, such a valley will be partially filled, made more shallow. Filling will proceed much as on a fan, the detritus will be dropped in the channel, some of the water will be displaced, new channels will branch out, in turn to become filled and have down-current branching develop, like distributaries. But the pattern of the channels is confined

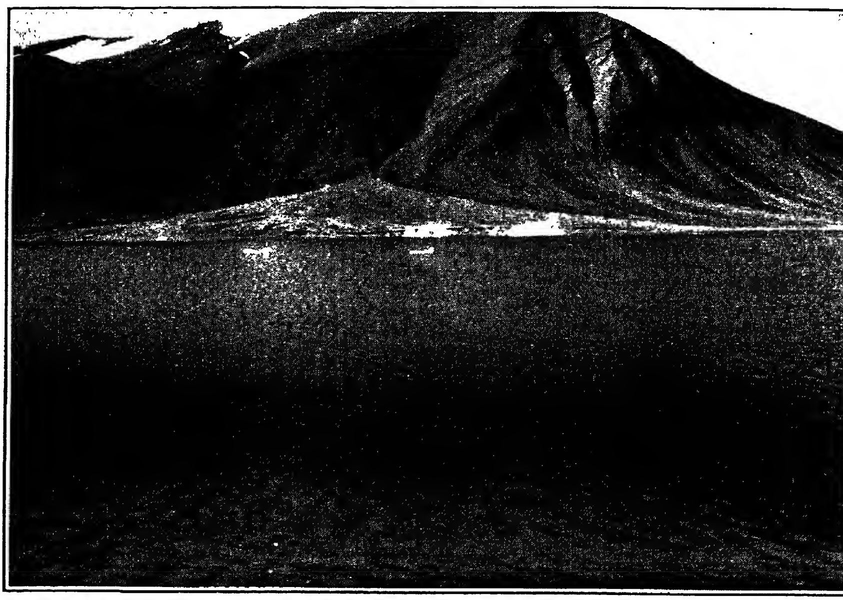


FIG. 65. Alluvial Fan, Franz Josef Fiord, East Greenland.

Or would you rather call it a delta? The more steeply sloped deposits on the right are talus fans. The head of the alluvial fan is half a mile back from the fiord and at least 500 feet above sea level. (Louise A. Boyd, "The Fiord Region of East Greenland," American Geographical Society, 1935.)

between valley walls and this forces re-unitings of the channels also, so a *braided* course results (Fig. 66). The valley will resemble one in maturity or old age, in that it will have a wide floor, traversed by a gently flowing stream. But it will be likely to differ topographically in other ways * and, if a deep alluvial fill is revealed by well drillings, there can be no mistaking its character.

* Name one.

FIG. 66. A Braided Stream Course among Alaskan Mountains.

So not all mountain streams flow in canyons, and not all are born of run-off from rain? (After Moffit, "Geology of Chitina Valley . . ." Bull. 894, U. S. Geological Survey, 1938.)

Overloading can result from one or more of several causes. Suppose the stream comes from high mountains and flows across an arid plain or plateau.* Suppose it is at the height of its ambitious budding out of vigorous young tributaries.† Suppose it receives the melt-water from an actively eroding glacier back in the mountains.

When the episode of overloading is past, the stream may be able to remove some of this alluvial fill by trenching into the deposit. Flat-topped remnants along the sides will then constitute *alluvial terraces* (Fig. 67), suggesting but easily distinguished from rock terraces.

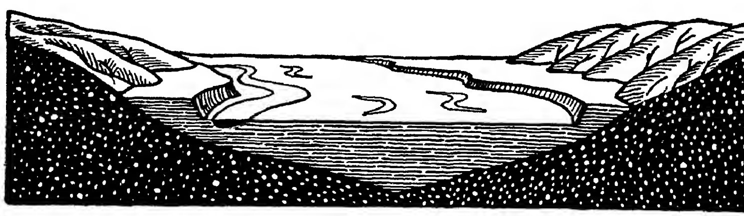


FIG. 67. Alluvial Terraces.

So the condition in Fig. 66 wasn't permanent? (After A. K. Lobeck, *Geomorphology,* McGraw-Hill Book Co., 1939.)

NATURAL LEVEES. Not an unusual form, but one somewhat surprising when first encountered, is the natural levee. "Levees" that figure in newspaper accounts of Mississippi River floods are artificial embankments built up along the channel edges to prevent the rising river from spreading out-of-banks across the fertile and populous floodplain. If the river does anything to these levees, it destroys.

But the river had levees long before DeSoto ever sighted it. They were not designed for a purpose; that's something nature lacks. They were a *consequence* of floods; they grew because the river made them. They held minor floods in the channel but not major ones. On them now stand the artificial levees you read about.

Never is any stream more heavily laden than in flood time. Since its bottom gradient isn't altered by the flood, it can

* Two causes?

† Remember the query under Fig. 36?

carry that greater load only because of larger volume, and higher velocity due to the larger volume. The flood overtops the channel banks, spreads widely on the valley bottom lands. The swirling rush in the channel is essential for the transportation. So soon, however, as the muddy water leaves the channel, its current is slowed. Down comes the excess load it can no longer carry. Sand, silt, and mud are deposited far and wide over the flats. The Nile's annual contribution of fertile silt to its floodplain, often cited, is an illustration.

Most of the sand and silt is dropped in the first mile, more or less; most of this up-building of the floodplain thereby occurs next to the river. The *natural levees* thus made are very broad and low, but they are higher than the rest of the plain. They are the last to go under in great floods, they are the sites of most roads, railroads, villages, farms. Actually, their own local runoff flows away from the river, into the floodplain's back swamps. And, actually, the surface of the river, confined between these natural levees, may be higher than the back swamps.

DELTAS. Fans, flats, levees; all are stopover stations for debris in transit. Sooner or later the streams will be able to give their material another ride. By trenching, perhaps, or by the writhings of shifting meanders. No stream quits work until its task is done; the piecemeal carrying of the land to the sea, the production of a surface so gently sloped that nothing more can be removed. That's the theory. Leaving streams alone to work out their destiny; is there any other possible end to their efforts?

The terminus of the journey is the sea.* Here comes, eventually, all the waste the river ever carries. Here is the end of the river's gradient. Here is the delta deposit, distributary-marked like an alluvial fan and, if composed of coarse material, having a perceptible slope like an alluvial fan. Even

* For almost all streams. There are exceptions. Nevada has some, so does Utah, so Arizona, New Mexico, and California. There's an unasked question here.

mud deltas and silt deltas have slopes, but a few inches to the mile looks perfectly flat.*

Delta growth increases the area of land, though at the expense of altitude. If the stream enters the head of a bay, the low land is advanced seaward until the bay may disappear. Islands off the coast may be reached, and surrounded, by the growing delta plain. Some seaports of the Middle Ages are now ten to fifteen miles inland, as a consequence of delta growth.

If some rivers do not succeed in building deltas, it is not because they contribute no sediment to the sea. If a delta is to be formed, more material must be deposited than waves, shore currents, and tide currents remove.

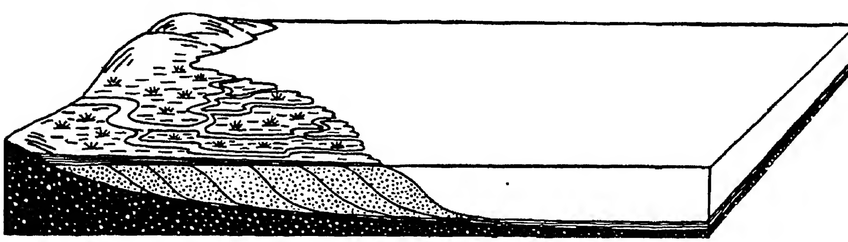


FIG. 68. Cross Section and Part of the Surface of a Delta.

Probably twice as many distributary mouths exist as are shown. Redraw, or add, to show the delta ten or a hundred thousand years later. (After Chamberlin and Salisbury, *College Geology*, Revised by R. T. Chamberlin and Paul MacClintock, Second edition, Henry Holt and Co., 1933.)

Most of a delta deposit is below sea level. The delta top has just enough slope to make the current necessary for carrying the material across and to its edge. It is the continuation of the floodplain slope downstream to the delta. Beyond the edge, its slope descending to the sea floor, is the angle of stability, as steep as the material will lie under water. It may be only three degrees for a mud delta, or twenty-five degrees for one composed of gravel. This angle between top and frontal slopes will distinguish a delta, whose water body had disappeared or been lowered, from an alluvial fan.

* The eye can detect a slope of about ten feet to the mile; less than that looks quite level.

SOIL EROSION AND RIVER FLOODS. If this were a book on man's relations to his environment, we would certainly consider in detail the pressing question of soil conservation. Man upsets nature's nice balance in many ways detrimental to his own interests, in none more disastrously than by cultivating the soil. In cutting off the forests and breaking up the prairie sod, he destroys the chief protection soil has. He then annually plows the cleared land, making the exposure to rain and running water still more complete. The rate of slope wash and gully growth becomes enormously accelerated, while the rate of soil making (weathering) remains unchanged. He could hardly proceed better if his purpose were to get rid of soil! Millions of acres of once good agricultural land have been utterly ruined by soil erosion in the last hundred years. Even if re-forested, they are agriculturally ruined for the next ten thousand years at least. Not alone has the fertile topsoil been stripped away, but the infertile subsoil has become gullied until these abandoned fields have become miniature badlands.

Nor is this the whole of the calamity. Overloading of streams has come from this excessive slope erosion, channels have become choked, floodplain farms have been ruined by the blanket of infertile sand and gravel swept out of the stream channels in flood time.

Many students of the problem believe that floods are greater today because cultivated uplands discharge their runoff more quickly than when they were grass-covered or forest-covered. Remedial measures are being tried under the national Soil Conservation Service. Some measures aim at checking the soil loss on the uplands, others at controlling the lowland river floods. Intelligent cultivation is possible in most regions, with conservation of this invaluable and irreplaceable asset of the soil. Other regions must be returned to forest land. They can still be cropped, but the yield won't be foodstuff. Cutting off of meanders and other straightening of river channels, making accessory channels for the floods, building bigger and better artificial levees, all will help the lowland situation in some places. Flood-control reservoirs, to hold back that levee-

topping last foot or so of a flood, are needed in other places. The work done by running water is truly a national problem of the first order.

ONE FLOOD. The flood of January, 1937. Headlines from newspapers over the entire nation!

THOUSANDS FLEE MENACE OF RAMPANT OHIO

RECORD FLOOD TO HIT LOUISVILLE TONIGHT. TERROR GRIPS AS DOOM APPROACHES ON RISING RIVER

BATTLE TO SAVE CAIRO. 4000 AT WORK ON LEVEE

WAR DEPT. MAPS RELIEF ON LINES OF MILITARY CAMPAIGN

RACE TO RESCUE 20,000 MAROONED

AIRLINES GIVE SERVICE FOR FLOOD RELIEF

FEAR ALL 102,000 RESIDENTS MUST FLEE EVANSVILLE

TROOPS PATROL LOUISVILLE

PLAN TO EVACUATE 500,000

OHIO VALLEY ONE VAST LAKE

CINCINNATI CUTS WATER SUPPLY TO AN HOUR A DAY

HOUSE APPROVES 790 MILLIONS FOR FLOOD AREAS, IF NECESSARY

Chicago Daily News, January 26, 1937. Front-page editorial:

"No catastrophe in American history has involved so vast an area or menaced so many people. More than 600,000 are already homeless. Gas and electric power are everywhere failing. Drinkable water is rationed and the supply is within hours of exhaustion. The specter of epidemic disease spreads wings of death above the deluge. The toll of life is growing every minute. The crest of the flood has yet to come. More rain is forecast. The Ohio River is nearly 25 miles wide at points along its yellow course. To predict 1,000,000 victims is to keep within the tragic possibilities."

For weeks metropolitan dailies carried front-page news of this flood. At its height, half the front pages and almost entire inside pages were devoted to the subject. Tank cars of drinking water were shipped to stricken cities from as far as Philadelphia and Chicago. Waves of influenza and pneumonia broke out. Sea planes brought vaccines. United States Coast Guard boats were shipped inland and operated on the new fresh-water sea in battling the flood. Amateur radio operators of the Ohio Valley worked twenty-four hours at a stretch in establishing communications, aiding rescue. Emergency armies of workers strengthened the levees, raising their level with sand bags to keep ahead of the unprecedented rise of the river. At Cincinnati the maximum flood rose eighty-one feet above low water level (when the river is ten to twenty feet deep), and covered one-fifth of a city built largely on hills. As the flood waned in the Ohio Valley, the Mississippi below the Ohio's entrance rose to an all-record flood stage, the crest advancing daily toward the Gulf. Finally, the flood passed out to sea, leaving 333 known dead in ten states, 1,035,000 homeless, and property damage of $400,000,000 in the Ohio Valley alone.

"Why the flood?" asked thousands outside the region affected. "One of nature's regular cycles, magnified from 250 to 400 per cent of normal intensity," answered the Weather Bureau. "The waters got their start toward the present flood fronts in the form of vapor carried in warm air blowing northward from the Gulf of Mexico. This moisture-laden air began its overland journey toward the Ohio Valley about January 1. It arrived over an area of some thousands of square miles from Pittsburgh to Memphis about January 6. On that day, nosing southward out of the polar Canadian region of the Mackenzie Valley was an equally great mass of frigid air. When these two opposing masses met, rain, snow, sleet, and ice storms resulted. And they continued, with rain predominating, over the entire area from about January 6 to January 25. This is a regular cycle of events. Every winter—in fact, about every two weeks each winter—warm, wet air

blows up from the Gulf and runs into a mass of cold Canadian air. The moisture is squeezed out of the warm air in the form of rain or snow. But this year the process has been stepped up in quantity and duration. Moreover, ground temperatures have been above freezing most of the time, permitting all the fallen rain or snow to run off in the form of water which seeks its natural drainage—creeks, rivers, and finally the Ohio and Mississippi." (See Fig. 69.)

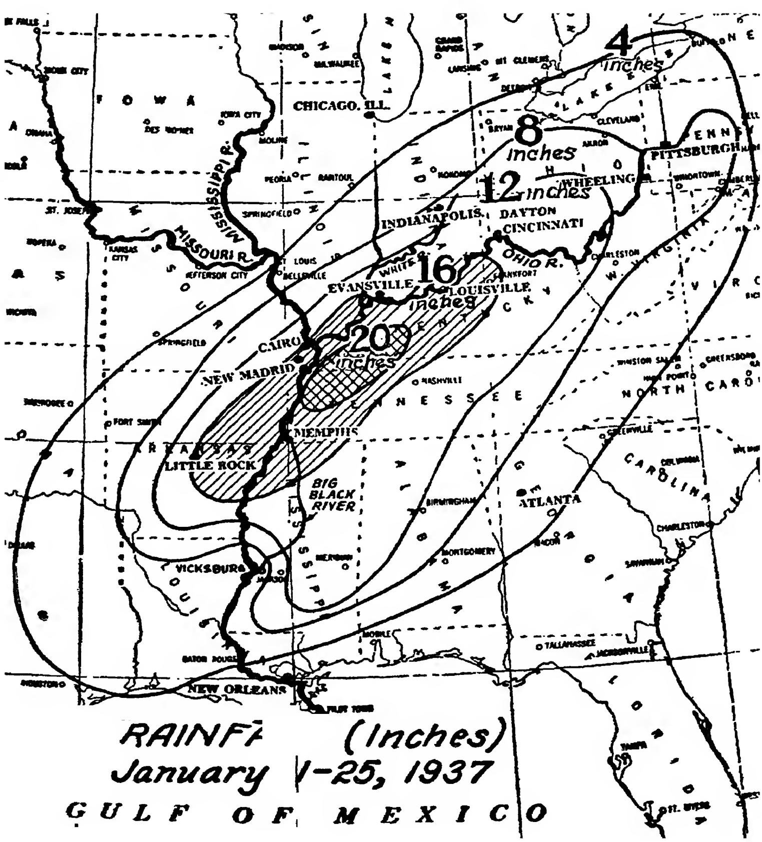


FIG. 69. Map of the Ohio river valley and Mississippi valley flood areas prepared by the United States Weather Bureau to show the amount of rainfall in various sections between January 1 and January 25, 1937.

SUMMARY OF RUNNING WATER. The "duty" of rain is to supply streams, soils, and the ground with water. At times this duty is terribly overdone. Yet most rain fails entirely in its duty by falling directly back into the ocean. Better not impute any purpose or plan or obligation.

The "results" of rainfall on the land—here we can stand on firmer ground—are rivulets, streams, soil water, ground water, and their consequences. The consequences of running water are almost infinitely detailed; this book contains only the ABC of them. But they all sum up in one grand result, destruction of the land.

At what rate?

River valleys are being deepened too slowly for us to measure. Most land is lowered by slope wash, anyway, and that is still slower. How would it do to go to the mouth of a great river like the Mississippi? What would you do there to get an answer?

Suppose you learned after some years of river gauging how many cubic miles of water were discharged annually by the Mississippi. Suppose you took samples of that muddy water throughout the year, in high water and in low water, let the sediment settle out, learned the average amount of suspended mud per cubic foot of water. Then you evaporated the water and learned the solution load. Still you would know only the total wastage; we wanted the *rate* of erosion.

The United States Geological Survey knew the next thing to do. They got the additional needed facts.* They concluded that, neglecting the material rolled along the bottom (and difficult to measure), the Mississippi system is lowering its drainage area by solution load and suspension load at an average rate of one foot in about 5000 years. Measurements from other rivers, averaged with this Mississippi figure, indicate a denudation for the entire country of one inch in 760 years. The average altitude of the United States is about 2500 feet. Figure it out yourself, and don't forget that this rate is the *present* rate.

* What information was needed?

Enormously slow? That depends on your measuring stick for time. Inevitable? If nothing occurs to interrupt it, the result *is* inevitable.

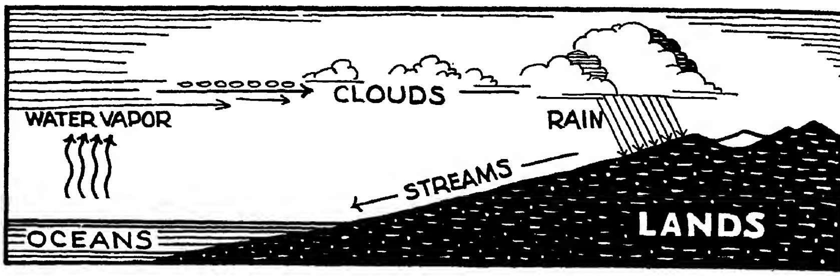


FIG. 70.

BIBLIOGRAPHY

AGAR, W. M., FLINT, R. F., and LONGWELL, C. R., *Geology from Original Sources,* Chapter VIII, Henry Holt and Company, New York, 1929.

LONGWELL, C. R., KNOPF, A., and FLINT, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology,* Chapter 4.

CHAPTER VIII

GROUND WATER

INTRODUCTION. The water that makes mud of the road dust or dampens superficial cracks in rock is soil water. It is very important in weathering and is indispensable for the growth of most plants. Very obvious today, it may be largely gone tomorrow, escaping by evaporation into the air. When supplied in large quantity by heavy rains, some of it moves downward beyond the limit of any later capillary lift back to the surface. Thus it becomes ground water in the proper sense.

There are none so ignorant or of such limited contact with our physical environment that they do not know that rain falls downward or that running water flows downhill. But there must be many who don't know that ground water comes from the rain, and that it percolates downward and laterally after entering the mantle rock. Else we wouldn't have that inexcusable proximity of wells and insanitary out-buildings in so many village and farming communities. Ground water is out of sight; hence, for most people, out of mind.

We must think of two zones of water in the ground. The upper zone rarely has all interstices full of water, the lower zone always has. Wells must be dug to the lower zone. They must end below the *water table,* the upper limit of completely water-soaked ground. Most mines and deep quarries are like wells except that they are kept pumped dry. An essential part of the mine and quarry equipment is a pumping system. Many mines are abandoned before they are exhausted because the mounting cost of pumping consumes all the profit.

Some wells may go dry during droughts but if deepened a few feet will again yield water though the drought be still unbroken. This can mean only that the water table became lowered during the rainless spell. It could have been lowered only because water was being lost somewhere, and not replenished. It's a natural loss, also, for there are too few wells and too little demand on them to cause the lowering. In whatever direction it went, the ground water escaped by moving away (i.e., it circulated, percolated, flowed).

Some regions make the answer to the problem very simple. They have springs and seepages, places where water flows or oozes out of hillsides. Wells up on the hill find water at higher levels than that of the springs. Even if there are no springs

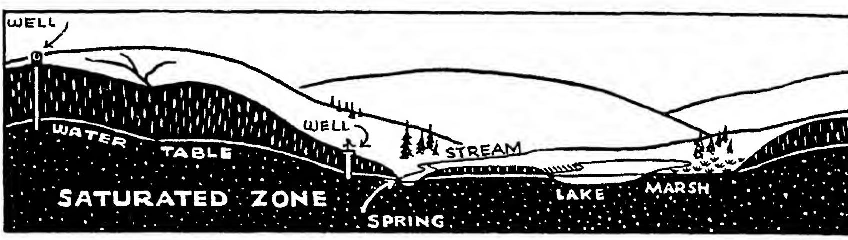


Fig. 71. The Water Table and Its Relation to Wells, Springs, Streams, Lakes, and Marshes. (After Chamberlin and Salisbury, *College Geology*, Revised by R. T. Chamberlin and Paul MacClintock, Second edition, Henry Holt and Co., 1933.)

on the lower slope, wells dug there encounter water-soaked ground at lower levels than those dug on the hilltop. There is, therefore, a literal mounding up of water under the hill, subparallel with the surface, and accumulated from the hill's own rainfall (Fig. 71). If it were out in the open, this mound would spread out and disappear in a minute. It does spread, even in the rock of the hill, but the pores and cracks are small, friction is great, and movement is therefore slow. The mound continues to exist because of repeated replenishments while constantly spreading and leaking away.

Springs. Springs and seeps are the visible leaks. If porous bedrock or mantle rock is underlain by impervious rock, and both outcrop on the hillside, the leakage is likely

to occur along the contact, a line of springs or perhaps only a greener growth of vegetation marking its position. Large springs are evidence of an extensive system of underground channels draining from a large upland area, rather than percolation from the ground water under a single hill. Our illustration was too simple a case to fit all springs; it was drawn to show only the fundamental principles involved.

Ice-cold springs are like ice-cold beverages, considerably warmer than ice. Indeed, spring water in winter is warmer than the creek water to which it flows, though just as cold as it was in the preceding summer. The vague and inaccurate statements you hear about the temperature of spring water can be very simply straightened out. Most ground water (wells and springs) has an unvarying temperature, whatever the season. It has the *average* temperature of the region, just as does the air of caves. If it is too deep to get warmed in summer, it won't get chilled in winter. Hot springs require a different explanation.

Spring water is reputed, also, to be pure water. What do they mean, pure? It certainly contains dissolved mineral matter, for it is "hard" and it leaves a residue on evaporation. And the filtering out of organic impurities, derived from the surface, is in no wise guaranteed just because it is a spring. Water moving down through large cracks and pores carries its bacteria right along with it.

LAKES AND SWAMPS. Some land surfaces have hollows or basins, undrained depressions, quite unlike the free-draining valley depressions made by streams, for higher land *entirely* surrounds them. We'll look into their origin later. Just now let's conceive of one whose bottom goes below the water table of the surrounding higher land. It is like a well in that sense, and similarly must have standing water in the bottom, water that has seeped out from the ground. Many lakes and marshes thus get most of their water supply from the ground.

PERMANENT STREAMS. We touched briefly, some pages back, on one of the relations of streams to ground water.

When streams, in deepening their valleys, have cut lower than the water table, they should flow during all but the worst droughts, should become permanent.*

INFLUENT STREAMS. Consider a stream flowing down from a mountain range, where there is adequate rainfall, and across an adjacent arid plain. The plain receives so little rainfall that its water table is far below the surface, much deeper than the bottom of the stream valley across it. This stream will lose by downward seepage to ground water. Perhaps you thought of this relationship in responding to a question regarding causes for stream deposition. Perhaps you may think that geologists should have called it an "out-fluent" stream.

ARTESIAN AND FLOWING WELLS. It is gravity which causes ground water to flow, and the pull of gravity is straight down. Almost the only water which flows straight down in the ground, however, is that descending toward the saturated zone after heavy rains. *In* that zone, there is a much larger horizontal than vertical component to all movement. So is there far more horizontal than vertical travel in any river. In both cases, escape can be found only in a lateral direction, and "water always seeks its own level." It is "downhill" in both situations.

Hence that almost universal need for the expenditure of energy (man muscle, windmill, gas engine, steam engine, electric motor) to pump water out of a well, against the pull of gravity. What are we to say about wells which deliver their own water, wells in which the water flows up and out? "Pressure," someone answers. That's right, but isn't it a bit too vague and too brief an explanation?

(1) Go back to the well-established fact that stratified rocks are generally uniform in nature *along* the bedding but exceedingly variable *across* it. (2) Recall that item about the importance of porous and impervious beds in localizing springs on

* Let the deepening continue in fairly porous rock. What reciprocal effect will that eventually have on the water table?

a hillside. (3) Remember that most stratified rocks have suffered movement since they were deposited, that slightly tilted beds are common. (4) Don't forget that the land surface in regions of tilted rock rarely parallels the structure, for greater uplift generally means greater erosion. If we can now arrange these four factors properly, we may say something more to the point than "pressure."

The flowing well is a drilled well, cased in steel pipe to the bottom. The drillers didn't stop as soon as they had penetrated to the saturated zone. They went deeper; they found rock so impervious that it yielded no water at all. They drilled on through that and beneath it they encountered porous rock containing water under such "pressure" that it rose up in the hole

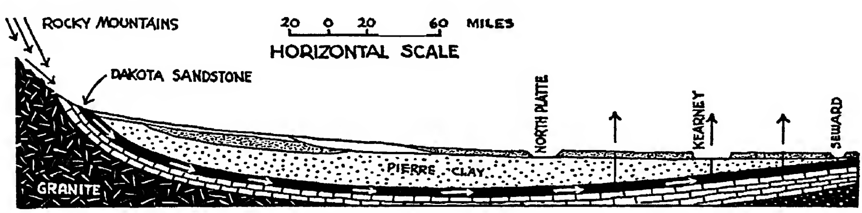


Fig. 72. The "Dakota" Artesian Basin in Nebraska.

Add arrows to show intake of rain and runoff water, (2) route followed by the artesian water underground, and (3) outflow from wells. (After Cleland's *Geology, Physical and Historical,* Copyright. By permission of American Book Company, Publishers.)

they had drilled (artesian well), perhaps up all the way to the land surface (flowing artesian well). It was as though they had tapped a subterranean water main! *

The water main they punctured must be a geological structure. Impervious layers above and below a porous stratum would do very well. Then there must be an entrance somewhere for the water which the porous stratum contains. And since the pressure is, after all, only a consequence of gravity, that entrance must be higher than the mouth of the well. Water can't enter through the overlying impervious bed, so somewhere the porous rock (probably sandstone) must crop out at this

* What generally causes pressure in a water main, and which way (up, down, sidewise) does confined water in a pipe flow?

higher level. This means that the impervious shale cover there has been eroded away. The land surface rises toward the higher intake area, and the rock structure rises still more! Now, check back and see if we have satisfied all four of those factors (Fig. 72).

Differences in height reached by artesian water in different wells, and differences in amount of discharge; aren't these all explained by differences in height of intake above well mouth, in distance between intake area and well, in porosity of the sandstone? *

Since heights, distances, and porosity do not change, any given flowing well can be depended on to yield at a constant rate—at least that's what they thought in the Dakotas forty or fifty years ago. But ask them about it today! Too tardily, state laws were passed to compel an owner to shut off his well when he didn't need the water. With an increasing number of wells and a continued thoughtless waste of the water, artesian pressure in the Dakotas has dropped, many wells have ceased to flow. Another one of nature's gifts has been all but ruined. The rate of intake in the Rocky Mountains to the west, and of transfer eastward down the dipping sandstone, was exceeded for decades. To close all wells for the next thirty years is impossible, and geologists say there is no other way ever to restore the original pressure and discharge.

SINKS. Springs commonly discharge clear water. Well water generally is clear. The velocity of ground water flow is inadequate for suspension of rock particles.† Ground water's work in removing rock material is therefore limited almost wholly to solution. Now, the minerals of most rock are almost insoluble, and, if there are soluble substances in them, they generally are in the zone of weathering where original

* With uniform porosity and uniform height of intake above well mouth, how will artesian pressure vary with increase in distance between intake and well? And why?

† The Wisconsin-supplied ground water for the artesian wells of the Chicago region is estimated to move half a mile a year.

minerals suffer decomposition. Thus, the mineral matter taken to the sea in solution comes in large part from the making of mantle rock.

Limestone, a fairly common sedimentary rock, is an exception to this rule. Limestone is a carbonate of calcium, precipitated (either chemically or through the agency of organisms) as a lime mud from a former state of solution in sea water. Consolidated lime mud (limestone), uplifted to become land and thus subjected to the searching infiltration of ground water, slowly redissolves in places of most vigorous attack. One place is just below the soil. Another is along cracks that carry circulating water. The solution of calcium carbonate rock is greatly aided by carbon dioxide dissolved in the water. Rain takes up carbon dioxide as it falls through the air. Even more comes from decaying vegetation, through which that part of the rain which becomes ground water may pass.

Most limestone is about as impervious as concrete. But concrete walls will leak, if cracked. Limestone possesses cracks, too; those deep cracks common to most rock, called joints. Water headed for the saturated zone descends along such cracks, dissolves the wall rock, removes the dissolved material, widens the crack. Most solution, and widening, occur in the upper part of the joint and thus a roughly funnel-shaped opening is formed, leading down to a tighter passageway for the water. Enlargement may so broaden the top of the funnel that the slopes will retain a soil, may become cultivable. This *sink* is not alone; there should be many of them on the surface of the limestone formation, so many in some regions that the only runoff is down their slopes into subterranean discharge ways. A sink may be less than an acre in extent, or more than a square mile. Depths may be only a few feet, may reach a hundred feet and more. Contour lines on their slopes will be concentric; they are closed depressions so far as the surface is concerned. They may contain lakes or swamps if and while their bottom exit is clogged with soil, dead vegetation, etc. Though rivulets may gully their slopes after cultivation begins, soil water and ground water have made them. They constitute

erosional work done on the land surface by water below the surface (Fig. 73).

C a v e s. Where does the water of a limestone region go after it reaches the saturated zone? It should discharge as it does in any rock, out from the higher land, toward the deeper stream valleys. Joints are long cracks and, even though vertical,

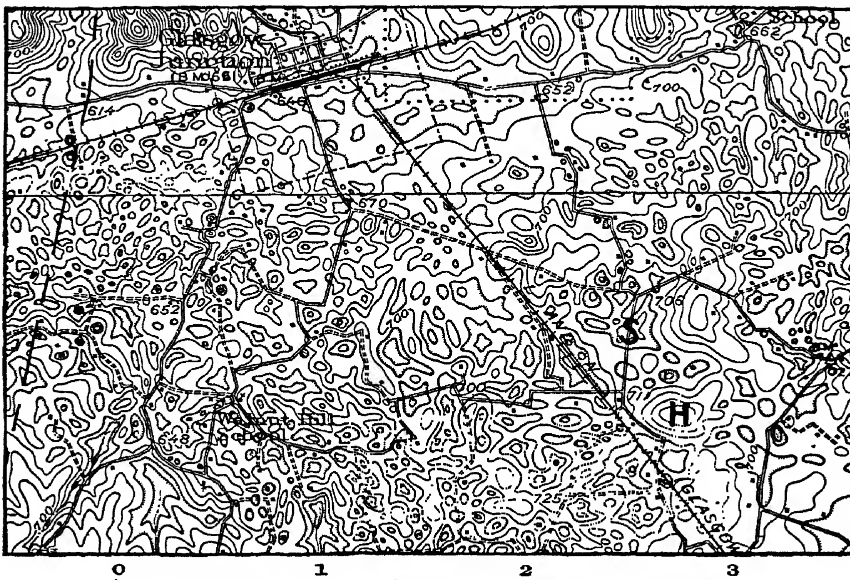


Fig. 73. Sinks near Mammoth Cave, Kentucky.

There are 500 square miles of this sink-hole-riddled country, without a surface stream of any importance. Sinks are hills in reverse, so their contour lines will also be concentric. Hachure marks on the contours (they're a bit difficult to see) indicate the holes. In the southeastern part of the map H is a hill and S is a sink. Contour interval, 20 feet. (U. S. Geological Survey, part of Mammoth Cave quadrangle.)

they can conduct water laterally out. Furthermore, the limestone is stratified, usually splits readily along the bedding, and may discharge its ground water in part along these planes.

Joints commonly occur in two systems of parallel cracks, oriented at right angles to each other. The bedding usually is approximately horizontal. Thus there exists a three-dimensional network of cracks which are potential routes for ground

water escape. They function as do the pores of a sandstone but they keep all the water of the rock to themselves. The rest of the limestone may be almost dry. Hence the solution of limestone will be limited to them. The most favored places for vertical descent (above the water table) will be at the intersection of two joints of each system. For lateral movement (below the water table), intersection of a joint and a bedding plane will be most favored. The greatest solution is likely, therefore, to occur along these intersections (Fig. 74). Along them will be developed a subterranean drainage pattern, in which smaller flowings will join and make larger ones. Solu-

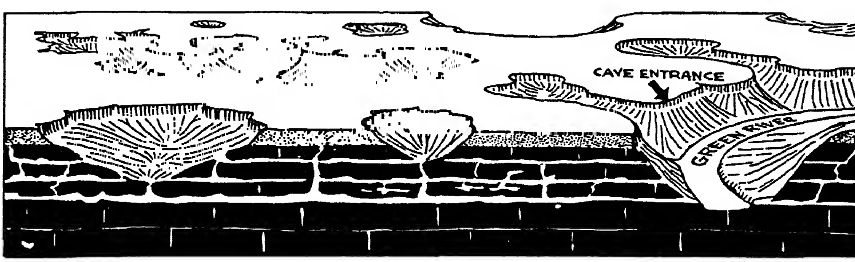


FIG. 74. Sinks and Caves at Mammoth Cave, Kentucky.

The valley of Green River is 300 feet deep. There are said to be 4000 sink holes and 500 known caves in Edmonson County, where Mammoth Cave is. (After A. K. Lobeck, "The Geology and Physiography of the Mammoth Cave National Park," Kentucky Geological Survey, Series VI, Vol. 31, 1929.)

tion will vary directly with the volume and rate of flow. *Caves* in limestone are the contemporaries of sinks, in part they are made by water the sinks first led down.

In the later history of ground-water solution in a limestone region, the caves may become huge affairs, perhaps with river-sized streams on their floors, but most of their cavity filled only with air. We may now come and explore them. We find in places great quantities of fallen, broken rock on the floors.* The stream promptly attacks and dissolves such rock—as long as a stream remains. Most caves you may visit, however, are dry. Stream channels may be decipherable in them but the streams are gone.

* Is that why the ceiling is so high?

This disappearance of former cave streams isn't because the region's rainfall has ceased or decreased, but because it has continued! Remember that running water is working also, that it is chiefly the deepening of stream-cut valleys that allows the escape of ground water. Most cave streams emerge as big springs in river-valley bottoms. That is to say, they are underground tributaries of the surface stream. We know that as a valley is deepened, its surface tributaries cut deeper. Underground tributaries may do the same, but they also have another option. Their water may drain vertically down the joints to a more favorably located bedding plane, which comes to carry the subterranean stream. A new horizontal tunnel or chamber develops, lower than the old one which becomes abandoned.

Competition * between surface streams and subterranean ones in a limestone region produces "lost rivers" and "sinking creeks." They are streams which discover a "swallow hole" in the bottom of their valley, plunge down to enter and enlarge a joint-and-bedding-determined cave that leads to some major river valley, probably the same one to which the stream was formerly a surface tributary. Resurgences or "rises" are those huge false springs where the lost rivers reappear. They are largely of surface water, swollen and muddy after rains, almost certainly unsafe for drinking.

Cave deposits. Water on its way down to the saturated zone may cross a dry cave, dripping in from its ceiling, filtering out through its floor. If this water is already well charged with calcium carbonate, partial evaporation in the cave air may cause precipitation. Stalactites (dripstone) may grow down like icicles from the ceiling, stalagmites (also dripstone) may grow up from the floor (Fig. 75). The floor itself may become plated with a crust of travertine (flowstone). The cave has begun to fill up again; a procedure which won't go very far, however, toward completion.

Destruction of caves. Ceilings of dry caves do not commonly possess smoothly rounded solutional outlines. The

* Or should I have written "cooperation"?

centuries have taken toll, slabs and blocks have fallen, the ceiling is likely to be rough and jagged, the floor may be a maze of fallen rock. Subtractions from the roof become additions to the floor, and the cave migrates upward in the formation. The roof may locally break through entirely, leaving a cliff-walled hole leading up to daylight, a *collapse sink*. Eventually so little of the roof may remain that the former cave becomes an open valley, with a *natural bridge* * across it.

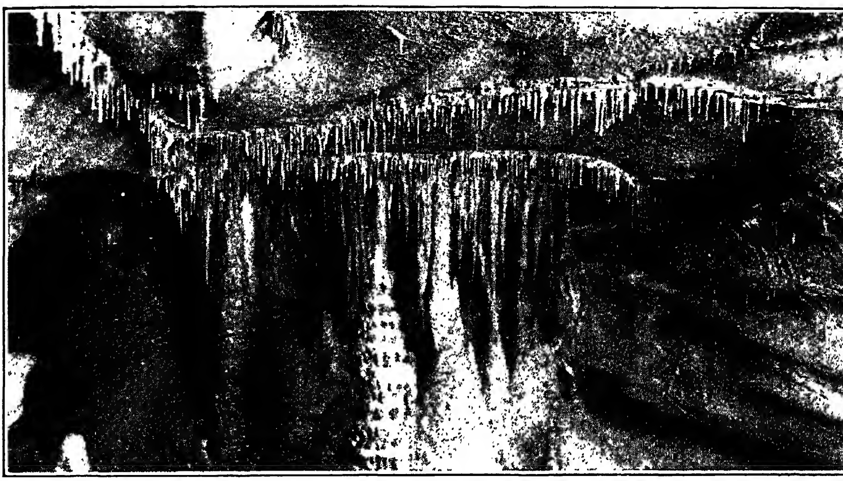


Fig. 75. Stalactites and Stalagmites in Mammoth Cave, Kentucky.

There is a definite reason for the arrangement in rows. (Caufield and Shook, Louisville, Kentucky.)

Caves in the cycle of erosion. A region that has limestone formations in its underlying rocks will presumably possess, in its maturity, the largest number of caverns.†

Hot ground water. That certainly is not water on its way down from the surface, nor flowing laterally out beneath the water table of uplands. Wherever it comes from, it is rising from considerable depths and its high temperature is

* There's no one correct explanation for all natural bridges.

† After that, the hills become ———, existing caves become ———, and even though the ground is full of water, ——— is lacking for much further cave-making.

decreasing as it rises. Hot well water, hot springs and geysers; these are rare in the experience of most people, for hot ground water near the surface occurs only in limited regions. Yellowstone has several areas of discharging hot water (some vents behaving like a steam engine's safety valve), and Yellowstone is a region of fairly recent volcanism. Iceland and New Zealand have similar areas, also related to recent volcanism. It's easy to understand why some of their springs are boiling hot, even though geologists tell us that the discharging water may have started down as thaw-water from snow. The igneous rock through which the water flows hasn't completely cooled yet. Other hot springs occur where there has been recent faulting, the line of springs coinciding with the line of the fault. Apparently, enormous friction caused the heat, and ground water is now helping to dissipate it.

The steam of volcanic explosions; isn't that an extreme case of hot ground water? Much of the steam discharged from volcanic vents is believed to have come from the magma itself, the mass of liquefied rock below the vent. It is believed to have been dissolved *in* the molten rock, to have been a part of the solid earth before the liquefaction which made the magma. It was never on the surface before; it is a new contribution to the atmosphere and hydrosphere.

Geysers. There are only three regions of those intermittently eruptive hot springs, called *geysers,* in the world (Fig. 76). In these regions, new geysers appear, old ones wane, some stop for a decade, then become active again. Very special conditions, very nicely adjusted to each other, seem necessary for geysers.

The boiling point of water in high altitudes; how does it compare with that at sea level? Ask some one who has tried cooking beans in a mountain camp! It follows from your answer that at pressures higher than fifteen pounds to the square inch, water must be hotter than 212° F. to turn to steam. An additional atmosphere of pressure brings the boiling point up to about 250° F.; two extra atmospheres means a boiling point of 275° F.

Geysers discharge from tube-like vents, their water coming up from depths unknown but probably a hundred feet or more. Each thirty-three feet of that depth means an added atmosphere

Fig. 76. Old Faithful in Eruption, Yellowstone National Park. (Haynes Inc., Yellowstone National Park.)

of pressure, a corresponding increase in the boiling point. The water is heated far down along the crack in the still-hot rock, under the weight of all water above it. If, when it does boil,

the steam bubbles rise and escape at the surface, we have no geyser, only a boiling spring.

If, however, the escape is retarded by crooks and constrictions in the passage, steam may collect (Fig. 77). The making of that steam causes some expansion in the fissure, lifting the

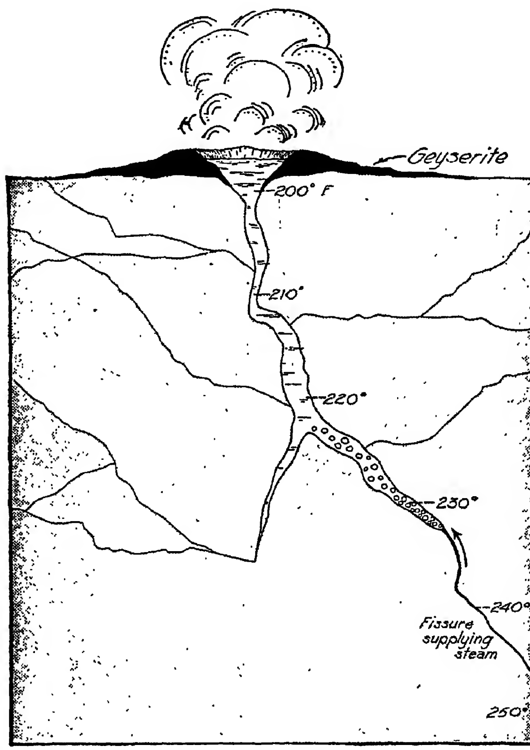


FIG. 77. Diagram of a Geyser. (Longwell, Knopf and Flint, *Outlines of Physical Geology*, John Wiley and Sons, 1934.)

water column, and causing a preliminary surging up in the geyser basin at the surface. Some tons of the upper water (32 cubic feet = 1 ton) may flow off on the surface or into adjacent upper fissures, relieving the pressure at the bottom by just that amount. With this decrease in pressure, the deeper water finds itself *above* its boiling point. It literally explodes, and this is the geyser eruption.

VEIN DEPOSITS. Veins are common things to the student of rocks. They are former cracks or fissures that later became filled with minerals deposited from ground water (Fig. 78). Evaporation isn't a very probable cause, as it is for dripstone and flowstone. Most commonly, vein minerals are deposited because the water cooled. That means that the water was rising, that the minerals were obtained at still greater depth. High temperature of the water was a primary requisite

FIG. 78. Veins of Gold-Bearing Quartz in a California Mine. (Longwell, Knopf and Flint, *Outlines of Physical Geology,* John Wiley and Sons, 1934.)

for their solution in the first place. High pressure doubtless aided. The water may have descended originally from the surface, or it may have been *juvenile,* i.e., derived from deep-seated magmas. Under this category of veins come many ore deposits. Vein ores may also be deposited by descending water, though something other than cooling must have caused the deposition.

The degrees of solubility of different vein minerals are clues to the direction followed by the depositing water, hence

are guides in the ever-pressing problem of "how much ore is left." *

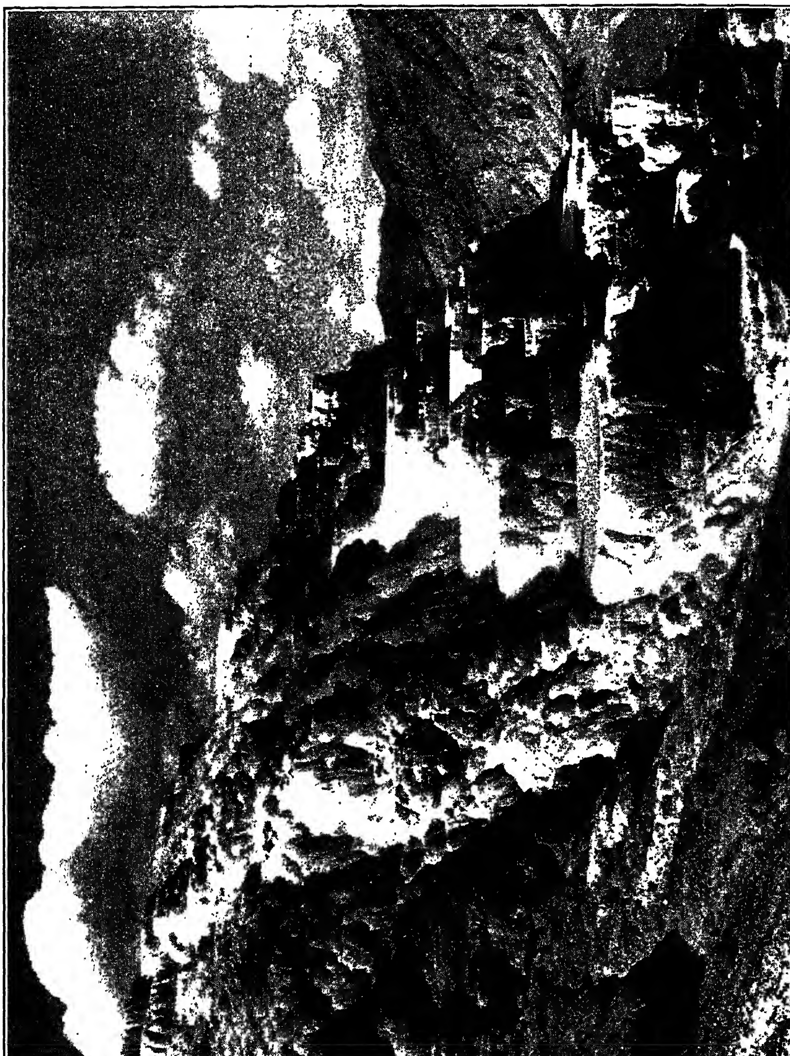


Fig. 79. Deposit Made on Hillside down Which Mammoth Hot Springs Flow in Yellowstone Park. (Union Pacific Railway.)

Spring deposits. Ground water is in such intimate contact with rock that never is there any lack of opportunity

* Would you advise investment and preparation for deep mining on an ore vein whose minerals record a downward-moving solution at the time the deposit was made?

to dissolve minerals. A large quantity in solution depends much more on high temperature and high pressure of the water and the presence of dissolved gases, like carbon dioxide. Escaping ground water may become cooler, certainly will have decreased pressure, and is likely to lose gases dissolved in it. Hence the extensive deposits of silica and calcium carbonate about geysers and hot springs (Fig. 79). Some ordinary cold-water springs also deposit calcium carbonate at the point of escape and perhaps for some distance downstream. Loss of carbon dioxide is probably the chief cause of this.

SUMMARY OF GROUND WATER. Most ground water is on its way back to the ocean whence it came. It left as water vapor, arrived on the land as rain containing dissolved at-

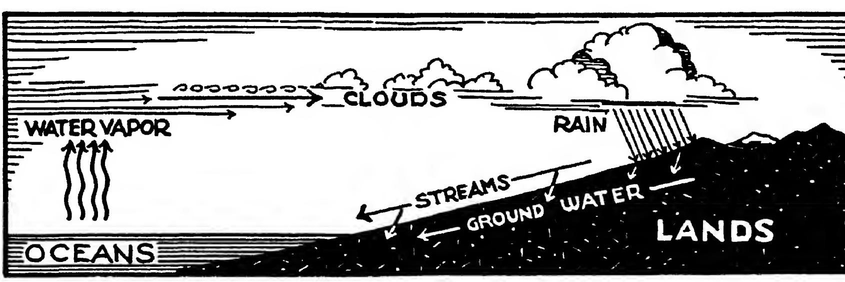


FIG. 80.

mospheric gases, went underground, promptly took up its search through every pore and crack for soluble minerals, will finally emerge from the ground with its plunder, join the surface streams, and return to the sea.

About one-fourth of the average stream load is dissolved material and most of this is contributed by ground water. Ground water alone is competent to lower the land by its method of erosion. Theoretically, there are no completely insoluble minerals. Given time enough, ground water could in the long, long run perform the task at which surface streams are considerably more efficient. Both work together, however; one can hardly exist without the other. The ultimate result of the combined attack, if uninterrupted, is destruction of rock,

transportation of the debris to the ocean, final disappearance of all highlands, the making of a monotonous low plain, the peneplain.

BIBLIOGRAPHY

AGAR, W. M., FLINT, R. F., and LONGWELL, C. R., *Geology from Original Sources,* Chapter V, Henry Holt and Company, New York, 1929.

ALLEN, V. T., *This Earth of Ours,* Chapter IV, Bruce Publishing Company, Milwaukee, 1939.

CRONEIS, C., and KRUMBEIN, W. C., *Down to Earth*, Chapter 9, University of Chicago Press, 1936.

HOBBS, W. H., *Earth Features and Their Meaning,* Chapter XIV, The Macmillan Company, New York, 1931.

LOBECK, A. K., *Geomorphology*, Chapter IV, McGraw-Hill Book Company, Inc., New York, 1939.

LONGWELL, C. R., KNOPF, A., and FLINT, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology,* Chapter 6.

LOOMIS, F. B., *Physiography of the United States,* Chapter IV, Doubleday, Doran and Company, Garden City, 1937.

CHAPTER IX

SNOW AND ICE

INTRODUCTION. An inquisitive college student once counted falling flakes in a snow storm. Ten to the square inch every fifteen seconds, he averaged. Multiplied by the duration of the storm and by the number of square inches Chicago covers, he concluded that the city acquired 8,510,717,952,000 flakes during that storm, an astronomic number. A week later there were none. All those 8½ trillion flakes had vanished as thaw water down the storm sewers, bound for the Mississippi and the Gulf. More significant than the number of flakes in that storm, than the total winter snowfall in Illinois, is that the snow doesn't remain; it melts and becomes runoff water and ground water. So it does in all our northern states, and in Canada.

Northward across Canada, the snow comes earlier and leaves later. The evergreen forests of spruce, balsam, and pine replace the more southern hardwoods, the "land of little sticks" is replaced by the treeless tundra of moss, sedge, and heather with "barren lands" on the higher, drier places. Shorter, colder summers; longer, colder winters; a harder struggle for existence, as we go north until in the little-known archipelago between the continent and the open Arctic Ocean, the winter snow does *not* all melt away in the summer.

The lingering snow at summer's end isn't soft and fluffy. Its surface was thawed during the summer, water soaked down into it, flakes have vanished; it consists of little pellets of ice like BB shot, like the snow of old drifts in our late winter, snow that won't pack into snowballs.

Think of ten years of accumulating left-over snow, a hundred years, a thousand! Ever thicker, more packed down, more like solid ice. How long can such an accumulation continue?

Not indefinitely, surely, else snow-ice would pile up to the sky.

The answer is found in the strength of ice. Winter ice castles several stories high will never be built, the lower ice blocks would "fail" under the load. Similarly, when this Arctic ice-from-snow becomes thick enough, it yields under its own weight and slowly spreads downgrade. We say it "flows," for it conforms to the slopes of the land, it may become concentrated in valleys. The movement, however, isn't much like that of a stream of water, nor of a mass of tar or wax. Better be non-committal than in error, and simply say that it moves downslope under the urge of gravity.

This is glacial ice, runoff in solid form, product of adequate snowfall in a sufficiently cold climate. Arctic lands discharge most of their precipitation this way, though summertime streams of melt-water also function. The Antarctic continent, more than half as large as North America, has streams only of glacial ice. It's too cold there ever to thaw! Every continent except Australia has glaciers in high altitudes where high-latitude climates are approximated. Even under the equatorial sun, in Africa, there are glaciers on Mt. Kilimanjaro, 19,000 feet above sea level.*

THE SNOW LINE. An indefinite, irregular, and varying boundary. Below it, both in altitude and in latitude, all the snow goes before summer ends. Above it, some snow remains in favorable places though much may have been lost by avalanching, by melting on sun-facing slopes, by drifting off wind-swept surfaces. Do not expect the snow line to be a contour line sharply marking off a region all snow-covered from one without any summer snow. The snow line is highest in equatorial latitudes, comes down to lower and lower levels in higher and higher latitudes until in the Arctic and Antarctic it nearly or quite reaches sea level.

VALLEY GLACIERS. Among mountains, snow generally accumulates most heavily in valleys because of additions

* The short polar summer isn't the whole explanation, is it?

from drifting off and sliding off the higher surroundings. If deep enough in these valleys, it is compressed under its own weight and becomes changed to solid ice (Fig. 81). A few inches a day, perhaps a few feet, this ice "flows" down the grade of the valley, down below the snow line, even down below the timberline. Obviously, it must eventually melt away. It cannot continue along the valley to the sea. How far below

FIG. 81. A Valley Glacier and Part of Its Drainage Area.

Crevasses mark tracts of "rapid" motion. Dwindling of the glacier is accompanied by increasing bulk of lateral moraines.

the snow line the glacier can extend depends on three factors: the rate of melting, the rate of advance, and the thickness of the glacier. But, beyond the limit reached by the ice, its substance, liquefied, flows on as a stream of water of much smaller volume* toward that destination all streams seek.

There are no glaciers among our eastern highlands south of Labrador, but many live in the higher valleys of the Rocky

* Why much smaller?

Mountains (Colorado, Wyoming, Montana), of the Cascade Range (Washington, Oregon, California), and of the Sierra Nevada (California). In British Columbia, valley glaciers are more common. Alaskan mountains facing the North Pacific Ocean have glaciers in almost all high valleys and many reach the sea, discharging icebergs instead of melting away on the land. Lofty mountains on the southern Alaskan coast force the moist winds from the Pacific to rise and become cooled; heavy snowfall is a consequence. That snowfall and the short Alaskan summer are causes for the marked glacial discharge.*

ICE CAPS. It seems probable that valley glaciers are a consequence, in part, of pre-existing stream valleys which collect the snow and guide the stiff ice streams. Large valley glaciers commonly have a few tributary glaciers arranged in stream patterns. A cover of snow over a region hasn't the mobility of a sheet of rainwater; it is likely to stay put on all but the steepest slopes. If concentration into ice streams is to occur, there must be drifting and avalanching; both conditioned by a preglacial topography of adequate relief and converging slopes.

Let's examine that idea further by reversing it. The region now to be considered has no stream valleys; it is simply an undissected plateau or dome-like uplift, standing well above the snow line. A mantle of ice develops until it is several hundred feet thick. The underlying slopes descend radially outward and on them the ice spreads out as an unbroken sheet. There can be no individual ice streams, hence no valleys can be *made by the ice,* and no valley glaciers will exist.

This type of glacier is not wholly imaginary. Though nature's plateaus and broad dome-shaped elevations are not as perfectly regular as those we imagined, there are many so nearly lacking in valleys, and now glaciated, that their ice covers them

* It's interesting to note that mountains of northern Alaska have almost no glaciers though they are within the Arctic Circle and a mile high. Your explanation of this fact may appear to forbid glaciers in Colorado and Montana; it does forbid a snow line in the Montana Rockies as low as in the Cascades of Washington.

like a cap, highest and probably thickest in the central part, flowing as our theoretical picture required.

ICE SHEETS. An ice sheet is simply a huge ice cap. Greenland offers a splendid example (Fig. 82). It is twice as large as Texas, and 86 per cent of its area is covered with ice which flows radially outward toward the coasts. In the central part, the ice surface constitutes a vast, gently sloping plateau ten thousand feet above sea level. That ice is more than eight thousand feet thick! * The outward movement is very slow indeed, for snowfall is not heavy (see Fig. 11) despite the suggestion the enormous mass of ice seems to give.

The rock surface beneath the ice in the interior of Greenland is low, the coasts are mountainous.† The rugged mountains which fringe the Greenland ice sheet are crossed in low places by the overflowing ice. Glacial tongues, thus formed, follow deep valleys to the sea. There they are broken up, like many Alaskan glaciers, by waves and tides, setting adrift that peril of North Atlantic shipping, icebergs (Fig. 84). Except in origin, these Greenland ice tongues do not differ notably from the great valley glaciers of Alaska.

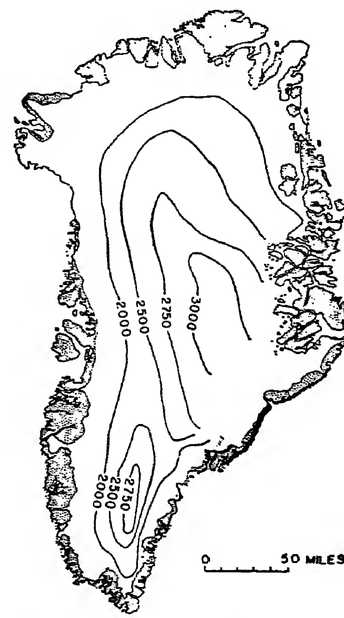


FIG. 82. The Greenland Ice Sheet. (Longwell, Knopf and Flint, *Outlines of Physical Geology*, John Wiley and Sons, 1934.)

* Determined by "echo-sounding" with explosives and seismographs (see p. 211). We said earlier that ice-from-snow never could pile up to the sky. In Greenland it has done something akin to this. It has accumulated until it rises above those troposphere levels in which most snow and rain clouds are formed.

† Ice moves downhill. How, then, is it possible for ice to move out from the central part toward the margin? (See Fig. 83.)

MORAINES. Conspicuously strung out on the surface of the glacier in the diagram (Fig. 85) is a long band of traveling debris. Trace that debris back to its source. It is *not*

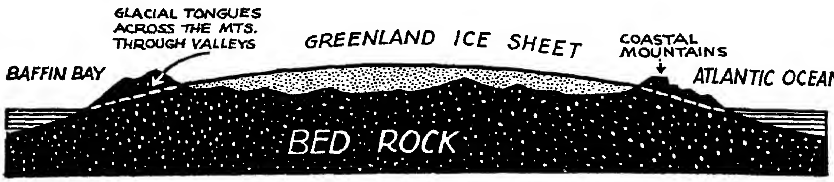
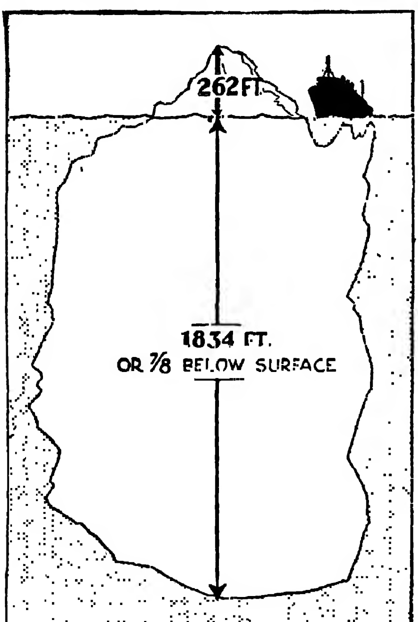


FIG. 83. Cross Section of Greenland and Its Ice Sheet in Lat. 70° N.

the mountain spur at the junction of the two tributary glaciers. That is only the take-off point. The debris had ridden some distance on the ice before it took off down the middle of the



What Is Wrong with the Newspaper's Diagram?

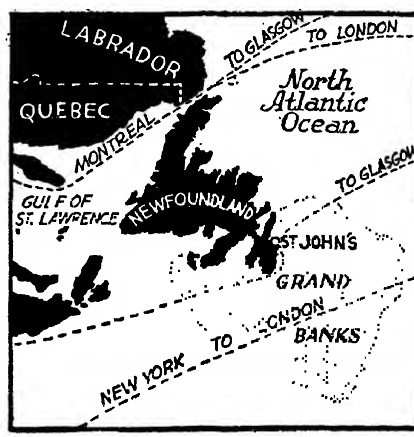


FIG. 84.
(Chicago Tribune, Thursday, Feb. 4, 1937.)

glacier's surface. If you consider those cliffs which the glacier is undercutting and which the nightly freezing and daily thawing of a glacial summer is attacking, there is no difficulty in understanding the source of the debris.

These ridges of detritus in transit are *moraines, lateral* if along the side of the glacier, *medial* if led out into the middle by coalescence of two tributaries.

In the foreground, the lateral moraines are very bulky. They stand much higher than the surface of the adjacent ice. They don't stand on the ice at all. Both laterals join in a curving ridge around the end of the glacier. We need another name. A *terminal* moraine is the deposit of debris made at the lower

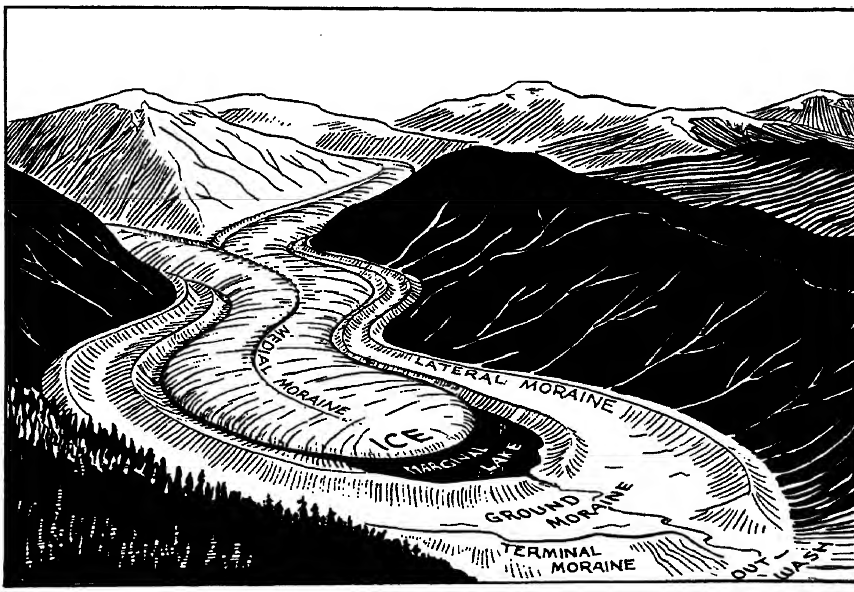


FIG. 85. A Valley Glacier and Its Moraines.

end of a glacier where, shrunken and wasted by a climate it cannot endure, it lays down its load and perishes.

Cliffed glacial fronts or ends (Fig. 86), uncommon outside the Arctic, afford a glimpse of the third dimension of glacial ice, the vertical. They show that most of a glacier's load is not on the surface at all, but is embedded in the lower part of the ice.* Obviously it was derived from rock beneath, not from

* Suppose such a glacier reached the sea and became broken up into icebergs. Now surely you can answer the query on p. 69 about a glacial record in mid-Atlantic mud.

cliffs above. It is the *ground* moraine and it is carried forward and added to the terminal moraine just as are the laterals and medials.

Ice caps and ice sheets may locally have mountain peaks and ridges rising through them, from which surface debris may come. But this is rare and these great glaciers generally have clean surfaces. Ground moraine material they have, and therefore they build terminal moraines.

FIG. 86. The load a glacier carries is mostly in the basal ice. (Louise A. Boyd, Photograph.)

OUTWASH. Melting occurs on the surface of the glacier as the ice is thrust below the snow line. The melt-water discovers deep cracks (crevasses), plunges down, enlarges the cracks by melting where the sun can't reach, develops subglacial routes somewhat as ground water makes subterranean routes in limestone. Generally a good-sized summer stream emerges from the glacier end, for all the ice fed down along the glacier has here been melted. It is an exceedingly turbid stream for the source, the glacial ice, is dirty, particularly in the basal part.

Crossing the terminal moraine, eroding part of it away, the stream carries off large quantities of waste contributed by the ice. It does one thing to this debris the ice can't do; it sorts it. Boulders and cobbles are likely to be left behind, gravel and sand travel down the valley until decreasing gradient causes deposition, silt and clay may continue in suspension to the sea. Deposition by glacier-born streams beyond the ice is like that in any other stream channel or on any floodplain. The *outwash* deposit is likely to be thick and to extend far down the valley, for streams fed by melting glacial ice are heavily loaded. Outwash is spread beyond ice caps and ice sheets by their escaping melt-water as it is in front of valley glaciers.

GLACIAL LAKE DEPOSITS. Melt-water streams that enter lakes may build deltas of sand and gravel like those made by normal runoff streams. The very fine mud, however, will cross the delta and keep the lake filled with opaque water all summer long. Winter stops the glacial melting, seals the lake under a cover of its own ice. There will be no waves, no currents, and no new mud supplied. The lake water may be almost clear by spring, the very finest of the mud having settled during the period of quiet. Now comes renewed glacial melting, renewed inpouring of muddy water, and therefore renewed deposition of mud over the lake bottom.

"Mud" is admittedly a vague term. We mean here a sediment whose particles are microscopic in size. You may again object, for that statement doesn't specify whether or not they are all of the *same* microscopic size. If not, the smaller ones will settle even more slowly than the larger, won't get to the bottom until the long quiet winter gives the needed opportunity. In the course of a year the lake bottom should receive a summer layer of "coarser" mud, and a thinner winter layer of the very finest sediment. Could we examine a section through this sediment (after the lake has disappeared and streams have eroded valleys into its bottom or men have excavated clay pits), and count all the pairs of layers (*varves*), (Fig. 87), we could

tell how many years the lake endured. It is very unusual to find actual years marked off in the geological record but varved clays afford one type of such a record.

FIG. 87. Varved Clay.

How many years are recorded in the exposed cliff face? (Satterly, Journal Geology, University of Chicago Press.)

CHARACTERISTICS OF GLACIAL DEPOSITS. Here is a deposit of sand (or sandstone, which is only cemented sand). Was it brought and left here by wind, by streams, or by waves and shore currents? Over there is a gravel deposit (or

conglomerate, which is cemented gravel). Did normal streams carry the pebbles there and drop them, or did glacial melt-water streams, or waves and shore currents? One might well be pardoned if he couldn't determine, for all these agencies sort out and stratify their debris, leaving gravel in one place, carrying sand farther along in their diminishing currents. But when dealing with a deposit made directly by glacial ice, we seldom need to say, "It *might* have been left by some other agency." Glacial deposits are distinctive.

There is no sorting possible. However slowly the ice moves, its fragments remain frozen in place. Big and little ride along together; the coarser never have stopovers while the finer ones travel on. When the ice melts, everything in it is left as heterogeneously mixed as when in transit. The largest boulders are embedded in a matrix of pebbles, sand grains, and that finest product of the glacial grinding, *rock flour.* There has been no weathering, as we ordinarily define it, to make this debris. There are no rusty brown colors from oxidized iron compounds, no carbonation of calcium compounds, no hydrated compounds, no solution changes.* It is freshly ground grist, purely mechanical in origin.

Further evidence of glacial origin is found in shapes of the pebbles and larger fragments. Rock fragments in a stream bed or on a beach are rolled over and over, any original angularity disappears, rounded shapes develop. But angularity and subangularity predominate among the glacially transported fragments. Still further evidence, and perhaps the most convincing, is in the markings on pebble, cobble, and boulder surfaces. The plane surfaces and their scratches, shown in Fig. 88, and the bevels where the planes intersect, could have been made only if the stones were held firmly by glacial ice and ground vigorously against each other or against the bedrock bottom while being transported.

Should we still be in doubt as to the glacial origin of the deposit, we should next examine its topography. Is it dis-

* Unless by weathering after the deposit was made.

tributed in moraine ridges, or as a sheet of ground moraine back of moraine ridges? Does it have *kettle holes,* those steep-sided depressions as big as a house or a whole city block, where buried masses of glacial ice have later melted out? Does it have the "dump" topography of hummocks, hillocks, hills, so

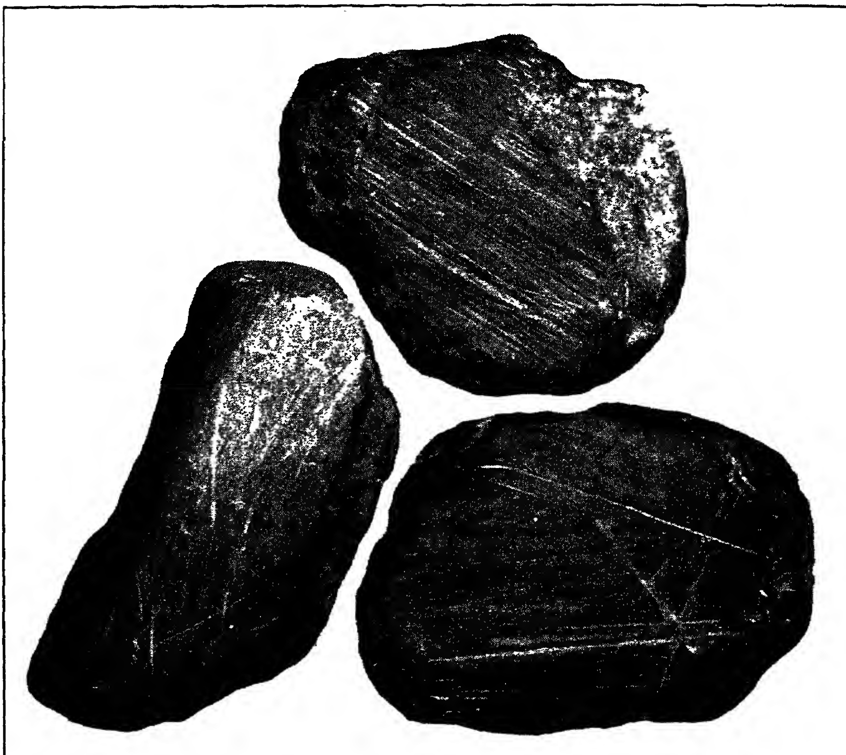


FIG. 88. Planed, Beveled, and Striated Pebbles from Glacial Drift of the Great Lakes Region.

disposed as to enclose undrained depressions? "Sag-and-swell," "swell-and-swale," "knob-and-kettle": these terms are used by geologists to describe the hills and undrained valleys that characterize moraine topography not arranged in simple ridges.*

* Warning! Sink-hole topography and dune topography superficially resemble moraine topography. But ——————.

MOVEMENT OF GLACIERS. Beware of confusion here, for two different ideas are involved. One is the movement of ice along the length of a glacier (analogous to stream flow). The other is the advance, or retreat, of the forward end of a glacier (no analogy in streams).

Glacial ice moves slowly. Only two glaciers have ever been reported whose ice moved as much as a hundred feet a day, and for both this rate was short-lived and under extraordinary conditions. The average rate is a few inches to a few feet a day. "Rapid" movement fractures the ice badly, produces great vertical fissures or crevasses. In "slow" movement, the ice goes over protuberances in its bed or around curves in its course without apparent fracturing. A row of stakes across a glacier becomes deformed into a curved line, convex downstream, as it is carried down the valley. The central part moves faster than the sides. There must be internal changes to make this possible, i.e., the ice isn't truly rigid when moving slowly.

Though glacial ice is as dense and hard as lake ice or river ice, it has the granular structure of old snow, corn snow as the skiers call it. It seems probable that these granules, under constant slow pressure, may rotate with reference to each other to give a semblance of flow of a liquid.

It is known, also, that the upper ice of a glacier moves faster than the lower. Nearly horizontal shearing planes have been identified in cliffed glacial fronts like that in Fig. 86, and the amount of shear has been measured. Upper layers slide over lower ones as the cards in a deck may be made to do.

Glacial ice, broken by crevasses, will heal again. Crevasses may be closed up later and the two sides may freeze together. Or water or snow may fill them and, becoming a part of the ice mass, obliterate the fracture.

It isn't correct, therefore, to think of a glacier as flowing like a slow river, or as simply sliding down its gradient. Complicated internal deformation must occur in the stiff, apparently rigid, mass, even though the evidence is convincing that at the bottom much actual sliding over the bed does occur.

Now let's consider the second idea. The glacier terminates downvalley because melting equals supply. Though the ice continues to move down the length of the glacier, the end may remain in the same place in the valley year after year. Should, however, a few years of unusually heavy snowfall occur, supply would exceed melting and the *front* of the glacier would advance downvalley until, with increasing warmth at lower altitudes, a new balance would be attained and a halt of the front would again occur. A succession of cooler summers might produce the same result. Decreased snowfall, or warmer summers, or both, would cause the glacial terminus to *retreat,* though the ice itself would be moving forward, down the valley, all the time.*

EROSIONAL RESULTS OF GLACIAL ICE. The pressure and friction beneath the moving ice of a glacier are great. Where joints in the bedrock cross the valley (especially if they dip somewhat downvalley) the glacier may break off or pull off fragments (*plucking*), which then act as tools for grinding away more rock. This erosion on a valley bottom is the source of most of the ground moraine debris. Its removal indicates that glaciers may notably deepen the valleys in which they flow.

The rock surfaces produced by plucking are likely to be rough and jagged. Grinding without plucking leaves smoothed surfaces, commonly covered with long, closely spaced, parallel scratches (*striae*) and grooves. No other agent of erosion leaves such markings. If the debris is fine enough and the rock of proper texture, a high polish may result.

Glaciers deepen the valleys they occupy more than they widen, making them over into steep-sided but rather flat-bottomed troughs. There is also a tendency to straighten out bends and angles in the valley course by undercutting the inside wall of the curves.

* Though the climatic change affects all glaciers of a given mountain range at the time it occurs, their fronts probably would not all begin advancing or retreating simultaneously. Two other factors are involved. What are they?

Thick valley glaciers know little about base level. If descending from a mountainous coast to reach the sea, they may erode the bottoms of their trough-shaped, canyon-like valleys hundreds of feet below sea level and, retreating later, allow salt water to follow the receding front back for miles inland. *Fiords,* thus formed, are characteristic of the coast of British Columbia, Alaska, Labrador, Greenland, Norway, southern Chile.*

A stream valley traced up its course is smaller and smaller until at its head it is little more than a ravine. Not so with that of a glacially eroded valley, which is likely to have the full width of the valley itself. The cliffed valley sides join in a cliffed valley head, the glacier deep-sunk in a natural amphitheatre out of which the ice flows downvalley. These are *cirques.* Mountain valleys without glaciers today but with cirque heads have almost surely been glaciated in the past.

Beneath the glacier, closely jointed rock and soft rock will be most readily eroded. The slowly flowing ice will be deformed under its own weight to fit down into depressions as they become excavated in favorable places and thus *rock basins* are scooped out along the valley bottom. We find them, generally filled with water, only after glaciers have retreated and abandoned the valleys they once occupied.

A glacier's relation to its valley is like that of a stream to its channel; the ice fills it from side to side and may fill it from bottom to top. A tributary glacier flows into the main ice stream; it doesn't fall into it. The surfaces of the two glaciers blend at their junction. But the tributary may be only half as thick (deep) as the main glacier. The bottoms therefore will not join accordantly, as the ice surfaces do. That of the tributary will "hang" above that of the main (Fig. 89). As with rock basins, we can see nothing of these relations until the ice has disappeared. Then streams of water, following the tributary troughs, will fall or cascade to reach the floor of the main trough. River-made valley systems almost never contain this

* They may be called drowned valleys. Their history lacks one item, however, that we generally include in the definition of a drowned valley.

relationship. Glacial modification is almost invariably responsible, and the returning streams do not tolerate it very long. When found with other glacially made earmarks, hanging valleys become part of our argument for former glaciation in the region, and a minimum expression of the amount of deepening that occurred during the glaciation.*

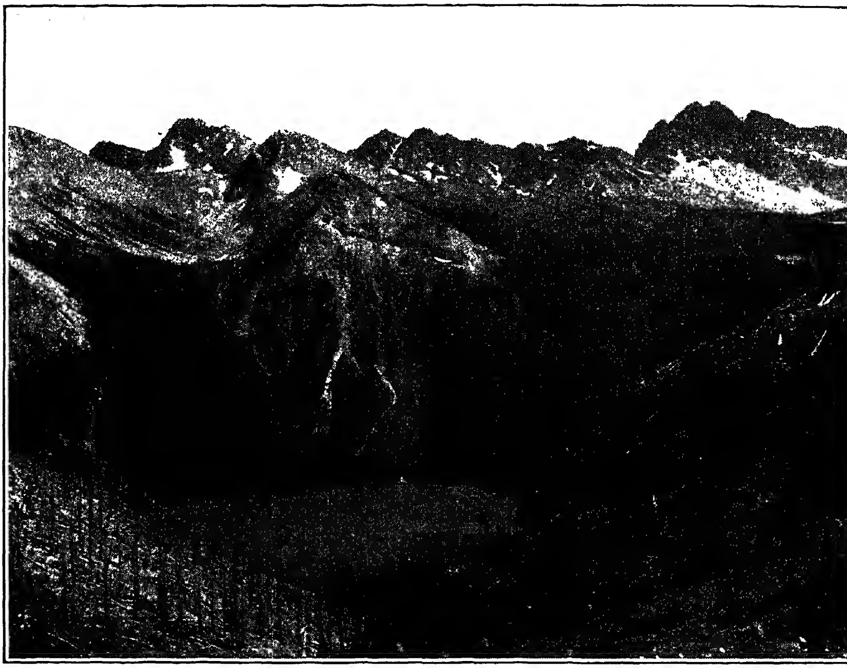


FIG. 89. Hanging Valley above Marvel Lake, in the Rocky Mountains near Banff, Alberta.

Running water has hardly started to trench into the lip of the hanging tributary. The lake lies in the deep main valley. (Canadian Pacific Railway, Photograph.)

FORMER GLACIATION. We don't covet glacial habitats for our own, we don't use glacial ice, we can't use glacial striae. Perhaps not one person in a thousand has ever seen a glacier. Why all these details about them?

First, because they are part of the gradational attack we are

* The tributary hangs, let's say, five hundred feet above the main valley floor. Why is this five hundred feet only a minimum measure of glacial deepening?

trying to outline. Second, because they are part of the scenery of several national parks, of many of our western mountain ranges. Third, because half the states in the Union have been covered, eleven of them entirely, thirteen of them partially, by a huge sheet of glacial ice.* The record is indisputable.

That last statement is too dogmatic. Certainly some one will dispute it; perhaps you know such a person, perhaps you are such a person. My paternal grandfather always said "Bosh," though the stone pile on his southern Michigan farm was made up mostly of Canadian *erratic* † boulders. If geologists tell us that the United States north of the Ohio and Missouri rivers and all of Canada have borne an ice sheet as large as Antarctica carries today, they must have evidence that satisfies them. What evidence would satisfy you?

Would you look for abandoned cirques and hanging valleys in the upper Mississippi drainage area or the Great Lakes region? Are lateral and medial moraines to be expected? Of course not; they require a mountainous area and valley glaciers. The record claimed as indisputable must be limited to features an ice sheet would leave on a region of low or moderate relief. Let's start again. Would you expect striated bedrock? Striated boulders and pebbles? Terminal moraines? Ground moraine? Outwash deposits? Erratics? Varved clay? Rock basins? Yes, even though some of these are erosional products of ice sheets, and some are depositional.‡

A saving clause was added, in a footnote, to one of our earlier statements about mantle rock. It is that not all mantle rock has "roots." The mantle rock of the northern half of our continent *does not grade* down into partially weathered bedrock, but rests with sharp contact on fresh, unweathered solid rock. Pebbles, cobbles, and boulders in the mantle rock

* United States histories don't record the extermination of this ice. The pioneers didn't drive it out with the Indians, nor kill it off with the buffalo, nor chop it down with the forest.

† Aren't we justified in so naming them if they have come *across*, instead of along, the St. Lawrence drainage, and *across* the St. Lawrence-Mississippi divide to lie now in the Mississippi drainage?

‡ Would you anticipate finding both in the same region?

are *not* all derived from the underlying bedrock. Geologists half a century or more ago puzzled about this. They found the bedrock surface in many places to be smoothed, striated, and furrowed by some mechanical action. They recognized boulders of granite in Ohio, Indiana, Illinois, where no granite in outcrops or deep wells had been found. They saw that the scratches in the bedrock varied somewhat in direction from place to place but on the whole were approximately north-south (Fig. 90). They argued that the mantle rock of the northern states (1) had not been made by weathering of local bedrock but (2) had been brought to its resting place by some transporting agent which failed to sort the debris, and (3) had traveled from the north along the direction of the scratches, because only in that direction were there extensive outcroppings of granite. Some guessed that the Arctic Ocean had been spewed southward in some gigantic convulsion, across the northern part of the continent, and that boulders carried in the hypothetical flood had made the gougings and markings. Others held that drifting icebergs, dragging bottom, had smoothed and striated the bedrock and, melting, had left the peculiar mantle rock. Glacial ice was asked for by some but few dared think of a climate in our latitudes ever so inhospitably cold and icy. That seems curious because they did dare think of an impossible cataclysm under the Arctic Ocean. The ice sheets of Greenland and Antarctica were then unknown, and former great expansions of existing valley glaciers were unappreciated. All called this mantle rock "the drift," committing themselves only to the fact that it had been transported. Increasing knowledge since that day of little fact and much fancy has made its origin abundantly clear and today we say "the *glacial* drift."

Plotting the measured striae on a map has shown that two great ice caps existed, one on each side of Hudson Bay (Fig. 91). They probably were much like the huge dome of ice on Greenland today. Their confluent ice was discharged northward as well as southward.* More than a million square miles in

* It got several times as far from the centers in which of these two directions?

Canada were scrubbed clean of mantle rock, had much bedrock plucked away and ground off. Glacial erosion occurred in southern Canada and northern United States also but, during waning stages of the glaciation, most of the eroded rock surfaces were buried beneath heavy deposits of glacial drift.

There were pauses in the retreat, recorded by a series of roughly parallel terminal moraines, the younger ones successively farther north and each with a corresponding ground moraine

Fig. 90. Glacial Deposit on Striated Bedrock. (After Chamberlin and Salisbury, *College Geology,* Revised by R. T. Chamberlin and Paul MacClintock, second edition, Henry Holt and Co., 1933.)

north of it. Outwash gravels filled many river valleys beyond the limit reached by the ice, and, later, as the halting retreat progressed, were deposited in front of each successive terminal moraine on earlier ground moraine (Fig. 92). The basins of the Great Lakes were formed during this glaciation; made over from pre-glacial river valleys. Where the land being exposed by retreat sloped northward, huge lakes were held temporarily between ice on the north and land on the south. One of these, in Minnesota, North Dakota, and Manitoba, was larger than

all of our present Great Lakes combined. Varved clays settled in these lakes, shore lines and deltas were made, outlets were

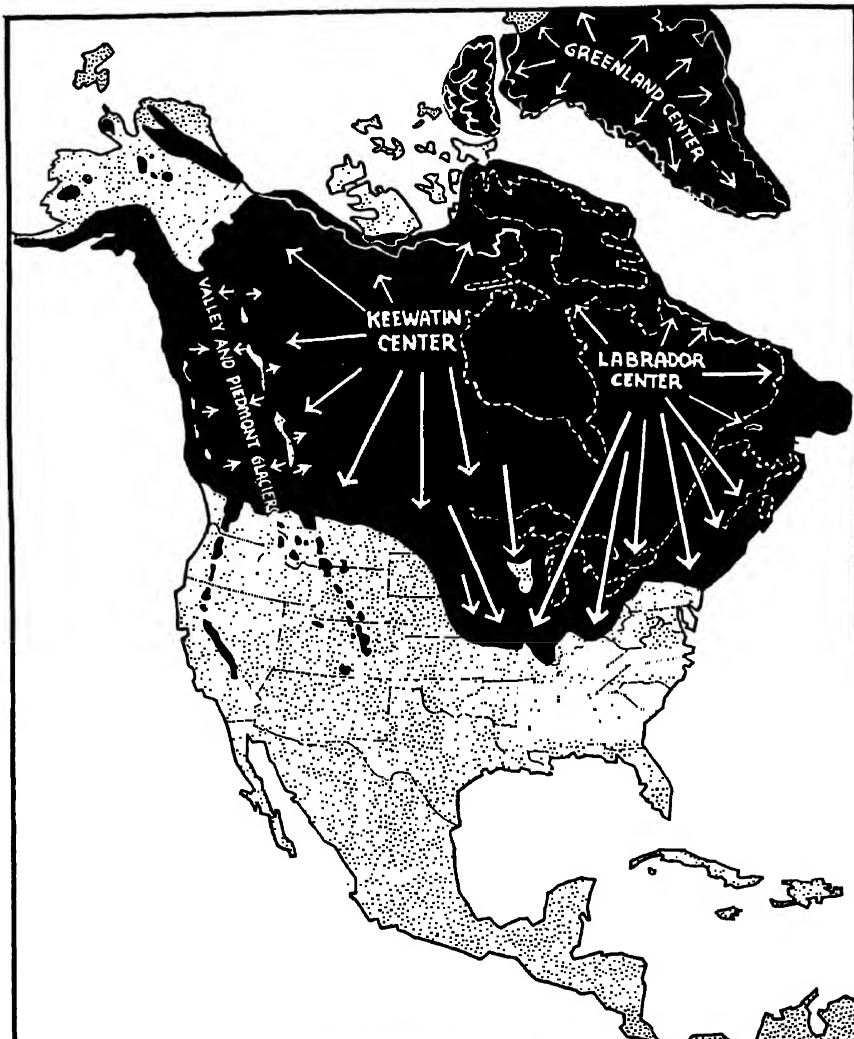


FIG. 91. Half of North America Was Once Covered by Glacial Ice. (After Schuchert and Dunbar, *Outlines of Historical Geology,* Third edition, John Wiley and Sons, 1937.)

cut. Rivers were re-routed, Niagara Falls was born, tens of thousands of lake basins were left among the irregular hills of the moraine belts.

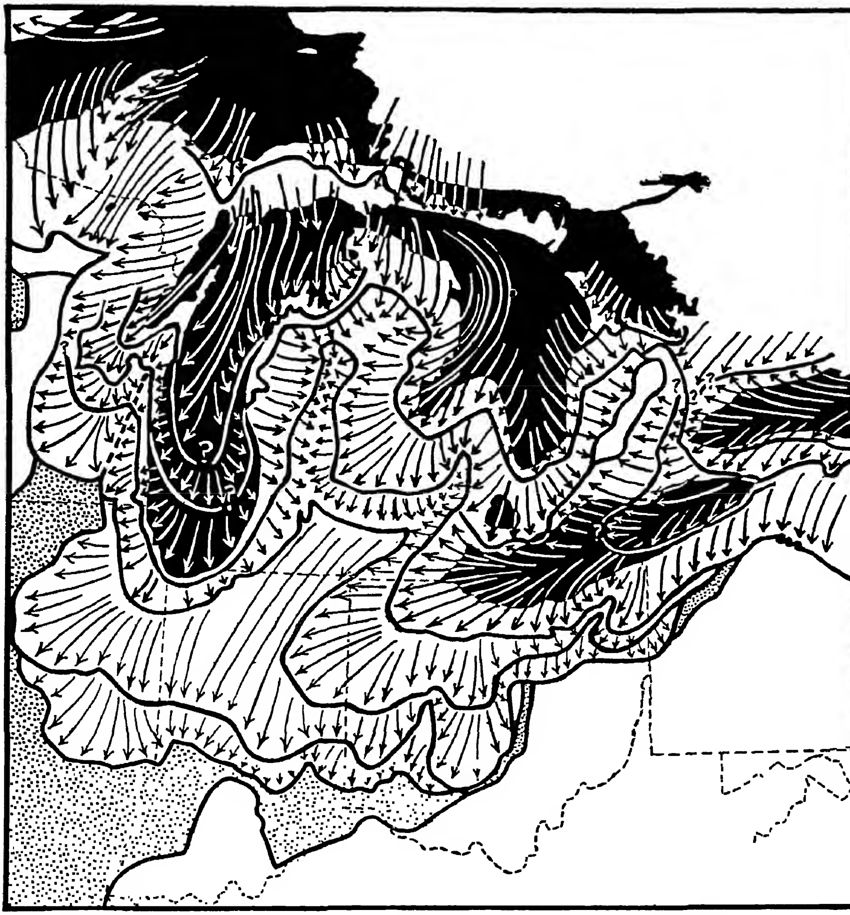


Fig. 92. Glacial Moraines about the Great Lakes.

The stippled area is covered by glacial drift older than any of the moraines. The white area south of the moraines has never been glaciated. Starting on the east edge of the map, trace the southernmost moraine westward as far as you can. Why does it have that northward loop in Michigan? How many older moraines are shown? Why do they not appear south of Lake Ontario? What probably explains the marked looping of the younger moraines? (After U. S. Geological Survey.)

These records still exist. The glaciation was so recent geologically that weathering and running water have made little progress in obliterating them.

Contemporaneous with this North American ice sheet was one in northwestern Europe. It spread from gathering grounds

on the Scandinavian peninsula across what is now the North Sea into Scotland and England. It invaded Germany by crossing *. . . the shallow Baltic Sea and spread widely in European Russia. Under the climatic conditions that gave rise to these two huge ice sheets, valley glaciers all over the world greatly increased in number. The two continental ice sheets have disappeared, many contemporaneous valley glaciers have gone with them, and all remaining ones are but shrunken remnants of what they were during the Great Ice Age.†

SUMMARY OF GLACIATION. A sufficiently cold climate is one requirement for glaciation. Another is adequate snowfall. Would a completely frozen earth have snowfall? Shall we not conclude that glaciation in one region requires

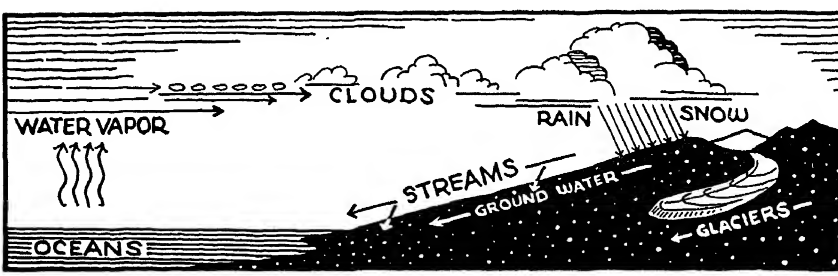


FIG. 93.

warmer climates elsewhere? That glacial erosion and deposition are special consequences of the great cycle, in which running water is the most important agent? With too much sunshine, glaciation is impossible. With *no* solar radiation, the same consequence. The destructive attack of glacial ice is but one method by which highlands are wasted away by our two-billionth share of the sun's radiated energy.

It is difficult to outline sequential stages for a glacial cycle of erosion. By deepening their valleys and driving their cirque walls back (through plucking at the cliff base), glaciers must reduce the area of high mountains which supply the snow.

* Displacing?

† The question you are now asking we can answer as yet only with theories. There will be something on them in later pages.

With decreased accumulation of snow, glaciation will wane and finally disappear. High-latitude glaciation, however, would not suffer this way; * only a climatic amelioration could remove its snow and ice. The North American and European ice sheets have disappeared, but it wasn't because they wore the land down below the snow line. In some way, the snow line was lifted.†

* Where is the snow line in high latitudes?

† Again, that question you asked and again the promise of some theories later.

BIBLIOGRAPHY

Agar, W. M., Flint, R. F., and Longwell, C. R., *Geology from Original Sources,* Chapter IV, Henry Holt and Company, New York, 1929.

Allen, V. T., *This Earth of Ours,* Chapter V, Bruce Publishing Company, Milwaukee, 1939.

Croneis, C., and Krumbein, W. C., *Down to Earth,* Chapter 10, University of Chicago Press, 1936.

Hobbs, W. H., *Characteristics of Existing Glaciers,* The Macmillan Company, New York, 1911.

Professor Hobbs has long been deeply interested in glaciers and in polar exploration. He has spent six summers in Greenland, on the edge of the ice cap.

Hobbs, W. H., *Earth Features and Their Meaning,* Chapters XX to XXVII, incl., The Macmillan Company, New York, 1931.

Lobeck, A. K., *Geomorphology,* Chapters VIII and IX, McGraw-Hill Book Co., Inc., New York, 1939.

Longwell, C. R., Knopf, A., and Flint, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology,* Chapter 8.

Loomis, F. B., *Physiography of the United States,* Chapter VI, Doubleday, Doran and Company, Garden City, 1937.

CHAPTER X

SHORE-LINE GRADATION

WAVES AND SHORE CURRENTS. We confidently explain most river valleys and their separating divides as the erosional result of the streams of the region, while glaciated valleys and their divides seem best explained as compounded of earlier land forms which the glacier later erosionally modified. In both, deposition plays a very minor part in determining valley and ridge character; for most of the debris yielded by erosion has been carried out of the picture. A consideration of shore lines must start with general features already provided (as with valley glaciers) and deal with modifications made by the shore agencies. But here we will find deposition alternating with erosion along a given shore in a fashion quite unlike anything we have yet encountered along other transportation routes.

The shore agencies are waves and currents. Winds and tides are their causes. The currents flow essentially on the level. Some reverse their direction from time to time. Comparisons with rivers and glaciers are going to be difficult.

Wave motion does not involve an onward movement of the water. Only the form travels, the water goes back and forth, i.e., round and round.* This is true so long as waves are out in deep open water. Remember also that wave motion extends down below the surface. This round-and-round orbital motion extends about as far below the surface as wave crests are separated from each other at the top. Waves, therefore, are something more than merely surface forms.

If open-water waves approach a shore, they encounter shallow water and drag bottom. This causes them to travel more

* See Fig. 23.

slowly. As the depth decreases, less and less water is involved in the wave, though the energy remains essentially the same. This makes waves grow higher. When the decreasing depth is no more than the wave's height, the top part of the wave outruns the rest of it, the form becomes unstable, and the wave falls forward or "breaks."

There is no transformation in a stream's or glacier's behavior to compare with the breaking of waves. Orbital motion is

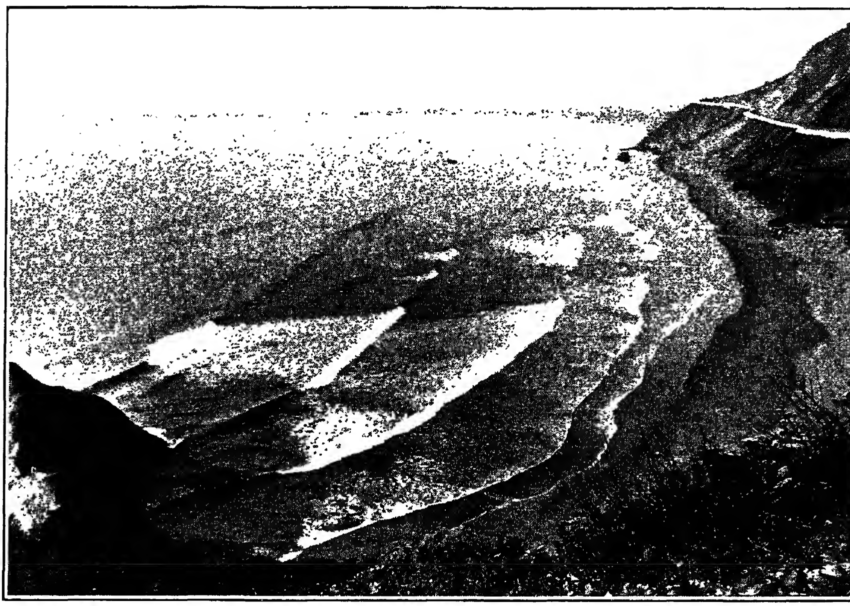


FIG. 94. Breakers Passing into Waves of Translation on the Coast of California.

Upper limit reached is indicated by the zone of wet sand. At full tide, these waves undercut the cliff. (Southern Pacific Railway, Photograph.)

completely destroyed and the water is thrown forward to advance as a horizontally flowing sheet against the shore. Thus the open-water waves of *oscillation* with orbital motion become waves of *translation* with only back-and-forth motion on the shore. On a low, gently sloping shore, it may surge many feet beyond the average water line, only to flow back down the slope to meet the next wave of translation. Several waves of oscillation arrive and break while this is taking place, so the

wave of translation is a compound effect and occurs at longer intervals (has a longer period) than do the waves of oscillation. With smaller waves or deeper water immediately offshore, breaking may not occur until the wave reaches the very shore line, the place where its existence ends.

Though waves are destroyed on encountering a shore, their energy, like John Brown's soul, goes marching on. Loose rock fragments, be they sand grains or cobblestones, are going to be moved. Moving, they wear and become worn. Finer material must be made by this grinding, too fine to stay in the agitated zone of breaking waves. Some energy therefore goes into mechanical abrasion. Some goes into transportation. Transportation requires a current. There are two currents born of waves breaking on a shore, each involving some of the energy of the destroyed waves.

Out in the open water, wind friction drags forward an upper film of water and blows "whitecaps" off wave crests into troughs ahead of them. Thus there is an actual forward movement of surface water under the urge of strong winds. Arriving at the shore, it is added to the water thrown forward as waves break. Water can't be piled up on a shore, it must flow down and back. The backflow beneath the waves, out into deeper water, is the *undertow*. Its velocity is generally overrated, for rarely do bottom slopes converge so as to concentrate it. But it will move fine materials from the beach-mill grinding out into deeper water.

The *shore current* comes from diagonal impingement of wind and waves on the land (Fig. 95). Not all the water then returns by the undertow, some of it moves along the shore line. It, too, will carry detritus but along the shore instead of away from it.

We must add that on some irregular shores, where bays with narrow mouths exist and where there is a considerable range between high and low tide, strong currents are produced * with no wind at all. These currents offer the opportunity, so long an unrealized dream, of putting the moon to work for us.

* Where?

They may vigorously sweep along parts of a shore line and act much as shore currents do. That they reverse is no objection to the comparison; so do some shore currents.

WAVE WORK. Storm waves may pound a coast line with almost sledge-hammer blows. Actually measured, they have exceeded three and a half foot-tons * to the square foot. Weak rock (soft or closely jointed) is beaten to pieces. The fragments become tools for further battering. Though constantly worn out and the finer waste carried off, the supply is constantly replenished and the attack is continually maintained.

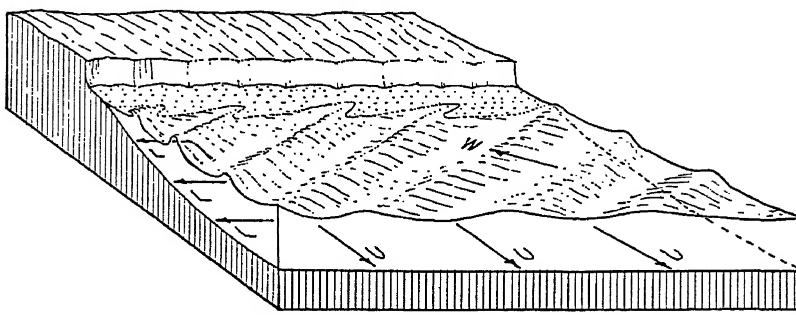


FIG. 95. Waves Diagonally Impinging on a Shore Line.

The arrows on the bottom and headed to the left, parallel with the shore, indicate the alongshore current. Undertow also shown by arrows. (Longwell, Knopf and Flint, *Outlines of Physical Geology,* John Wiley and Sons, 1934.)

It is a hydraulic excavating mechanism of hammers and sluiceways.

Sea cliffs. This wave attack operates along the water level, undercuts at that level (Fig. 96). Rock is rarely strong enough to maintain the overhang above the niche. Commonly it slides, crumbles, breaks and falls constantly, and a cliff results, a *sea cliff* (Fig. 97) made by wave erosion. The victorious waves drive the sea cliff back, the area of land is decreased, that of the water is increased.

Wave-cut and wave-built benches. Waves have a lower limit of effectiveness, below which there is almost no removal of material. Hence a shelf is left as the sea cliff recedes, a *wave-*

* Equivalent to three and a half tons falling a distance of one foot.

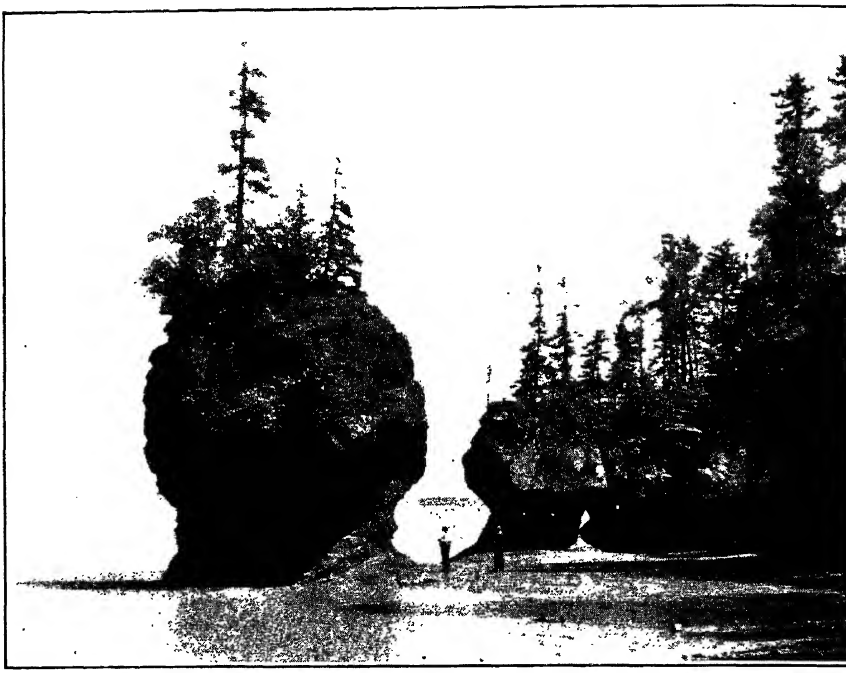


Fig. 96. Niched or undercut sea cliff, with isolated "stack." Hopewell Cape, New Brunswick. (National Development Bureau, Department of the Interior, Canada.)

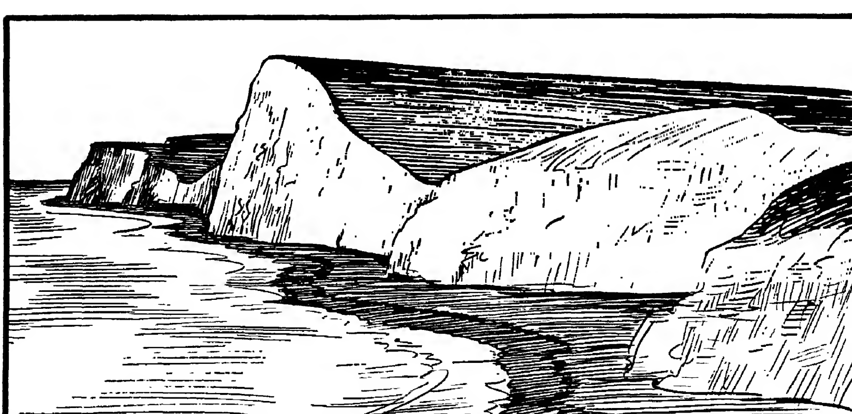


Fig. 97. Retrogradation here > Degradation.

The evidence is undeniable. Chalk cliffs of Southern England. (After *The Scenery of England,* Lord Avebury, The Macmillan Co., 1902.)

cut bench, under the area newly gained for the kingdom of the sea. Waves drag bottom across it, sediment on it from the shore is constantly disturbed and shifted about, eventually finding its way to the offshore edge and (Fig. 98) dropping below the depth-limit of waves, where it is relatively safe from further disturbance. The *wave-built bench,* thus formed, is a continuation of the wave-cut bench, both submarine, both con-

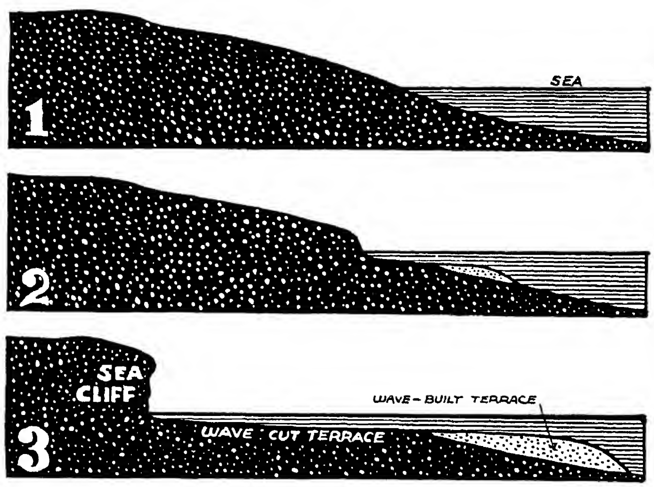


FIG. 98. Development of Sea Cliff, Wave-Cut Terrace and Wave-Built Terrace. (After Emmons, Thiel, Stauffer, and Allison, *Geology,* McGraw-Hill Book Co., 1932.)

comitants of the sea cliff. Soundings and dredgings inform us of their existence. Low tides may expose part of the wave-cut bench.

SHORE CURRENT WORK. Think of an irregular shore line, margining a hilly land. Numerous bays mark the valleys, peninsulas mark the divides. (See Fig. 33). The peninsulas are much exposed to wave attack, the bay shores are more protected. Sea cliffs therefore will not occur all along the coast line. Their development will be most marked on the peninsula ends. This means that the largest amount of detritus from wave erosion will be produced there. But it won't stay. From whatever direction the wind comes, it and the waves must meet some part of the shore diagonally, and shore currents are inevitable,

currents that will lead back somewhat into the bays before shoaling water and weakened waves decrease them. Their work will be the transportation of some of the debris from sea cliff bases along the peninsula shores and back into the bays.

The shore current, born of wind and waves, is not deep. Along the shallow shore water, where waves maintain a fairly constant agitation, it will add a prevailing urge in one direction as the sand grains and pebbles are tossed and rolled about. With many stopovers, as in a river, the particles will travel along the shore and back into the re-entrants of the coast.

SPITS AND BAY BARS. Here in the bays the current weakens and here the material must be left. A wide beach may be built out in front of the original bay shore, advancing the land at the expense of the water. Or a *spit* may be built. A sand spit or gravel spit is a very striking feature to those who have never before seen one. It is a long narrow ridge, mostly under water, projecting out from the shore at a low angle into the bay. It may appear out of harmony with other shore features, even artificial, and one may wonder how it (Fig. 99) survives destruction by storms. But it is in perfect harmony with, and a necessary consequence of, the changes being wrought by the shore agencies. Storms helped to make it.

The one thing required for growth of a spit is that the current *leave the shore*. That's not as extraordinary as it may seem. The chief current-generating condition is a diagonal approach of effective wind and waves, the direction of whose approach may be, within a few points of the compass, fairly constant on a given shore. But suppose that the shore line, farther along in the direction the current flows, has a landward bend in it so great that, beyond the bend, the current has no shore line to hug. The current must go on, out into open water.

Debris carried by the current goes out with it until, in the deepening water, the current no longer touches bottom. Here the debris must be dropped. Depth is thereby decreased until again the current drags bottom. Debris can now be carried a

little farther. The initial spit was a projection of the beach; it becomes longer and longer, a ridge no higher than the reach of storm waves but growing by constant additions on the tip until it perhaps extends completely across the bay, makes a lagoon or lake of the headward part of the bay. We then

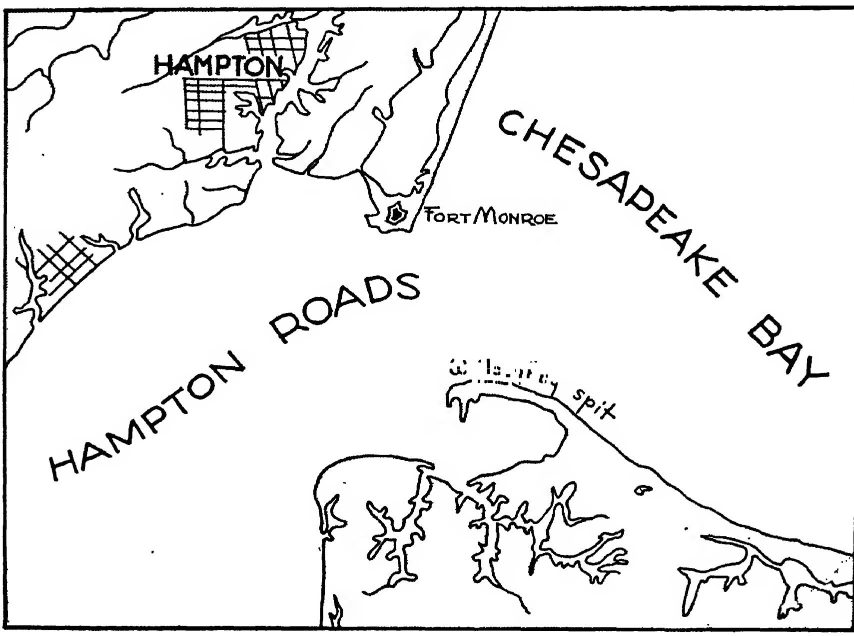


FIG. 99. Hooked Spits on the Virginia Coast.
Hampton Roads is a small bay-like drowning of the mouth of James River.

cease calling the embankment-like deposit a spit; it has become a *bay bar.*

There is almost infinite variety among spits; in locations, shapes, sizes, but the principles governing all of them are the same. If one walked around the bay we have been considering, from the headland on one side to that on the other side, he would pass from a shore line of erosion (sea cliff, submerged wave-cut terrace, coarse detritus on the shore) to one of deposition (beach, spit, or bay bar), the beach material becoming finer and the particles more rounded farther back in the bay, and then would encounter the reverse of this as he approached the other

headland. Along such a coast line, one finds repeated alternations of erosion and deposition.*

BARRIER BEACHES. We have been thinking of the shore line of a hilly land. The coasts of Maine, Massachusetts, Washington, Oregon, California; all of these would qualify. By way of contrast, let's consider the shore line from Maryland south to Florida and all the way around the Gulf of Mexico to and beyond the Rio Grande. It isn't the same everywhere but it all has one common character; it is the seaward border of a low coastal plain. There is little detailed irregularity in outline. Bays are broad and shallow. If there are any sea cliffs, they are few and low. Long, narrow sand islands or *barrier beaches* face the sea, enclosing lagoons and salt-water marshes between them and the land. The water offshore is shallow. The region obviously had a different history before the shore agencies started work, and those agencies have had to operate under different conditions.

We notice immediately on inspecting Fig. 100 that one barrier beach may serve to close several bays off from the sea, the barriers not touching the peninsula tips but standing far enough offshore to leave a long, narrow lagoon connecting the bays. We notice that, though many of the barrier beaches are tied to the mainland, they show little if any inclination to bend inland on crossing bay mouths. Instead, they line up with the general course of the shore line. Those connected to the land look like spits but surely can't have the same origin as those which grow back into bays from the wastage of adjacent headlands. Significantly, many of the barriers are not tied to the land at all.

In explaining barrier beaches we must not forget two important features which the map does not show: the sea is shallow, and the beaches have no coarse material. We must add also that incoming large waves break before they reach the

* River valleys seldom show this. There the rule is for most erosion and coarsest debris in headwater portions, decreasing erosion and finer debris farther along, then a floodplain where erosion and deposition are about balanced, and at the end a delta where all is deposition.

shore.* Between the breakers and the land the bottom is swept by waves of translation. Sand there is carried landward and is dropped as this wave weakens and dies, until a long low ridge is built in front of bay and peninsula alike, rarely con-

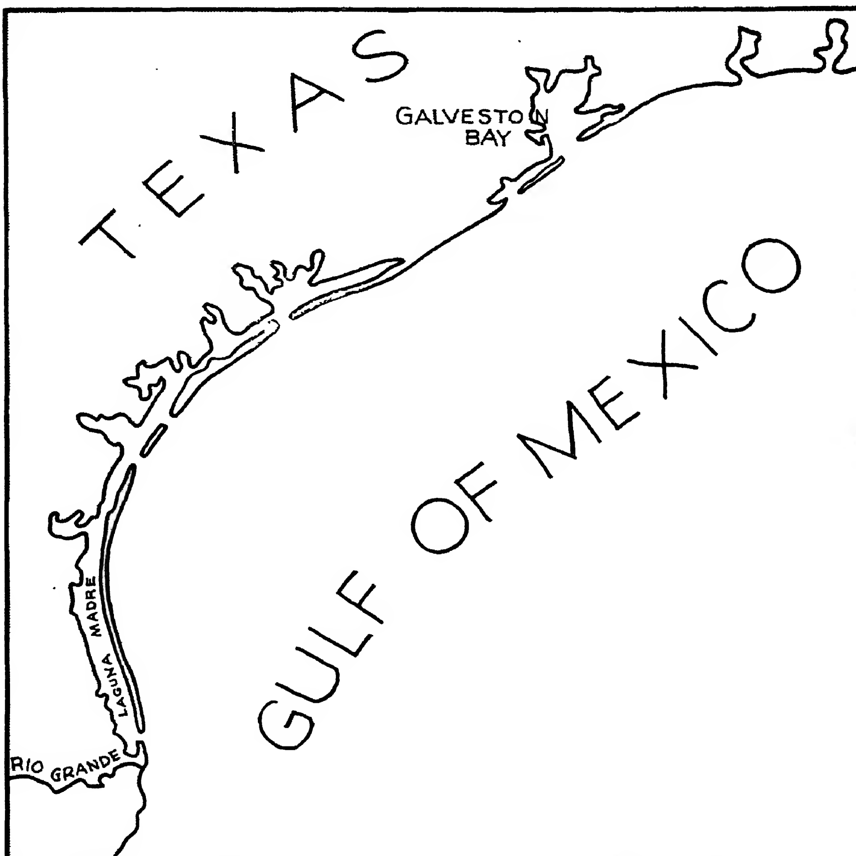


Fig. 100. Barrier Beaches along the Coast of Texas.

nected above water with the mainland. Its material has come from the shallow bottom offshore, not directly from the land.

Shore currents are not barred from the picture; indeed, those spit-like beaches in Fig. 100 argue strongly for their participation. But there is no such striking localization of source mate-

* The larger they are, the farther out is the line of breakers. Why is that?

rial and of place of deposition as there is on the irregular coast of a hilly land.

Lagoons behind the barriers may be so filled in as to become marshes in time, even dry land. *Offshore bars,* produced by the line of breakers and familiar to all who swim or boat on such coasts may grow beneath the water until they become the site of new barrier beaches. If so, such coastal lands are being built out, the sea off them is losing ground.

Reversing shore currents were mentioned earlier. Don't the spit-like barrier beaches in front of Galveston Bay, Fig. 100, suggest them? All the theory needs is that some effective winds come from points between east and southeast, some from the south and southwest.

PROGRADATION AND RETROGRADATION. Where deposition by currents occurs on a shore line so extensively that the land area is increased and that of the sea diminished, *progradation* is occurring. Delta growth might be included under that term but it also belongs to the analogous procedure of aggradation, the building up and filling up, by any agency, of low places on the land.

Retrogradation (retro, Latin for back, backward, behind) occurs where part of the land is sacrificed to waves and currents, where the shore line is driven farther inland, where the area of the sea is increased. It is analogous to degradation, lowering of the land by wind, water, glacial ice.*

TWO TYPES OF INITIAL SHORES. Every gradational agent, launching out on its task, inherits a topography which must be redesigned to fit its needs. It deepens here, widens there, even *raises* the grade if necessary. Changes in outline of shores are clear evidence that the inherited, original shore line was not acceptable, not harmoniously proportioned to the forces which came into possession. How do original shores come into existence, anyway?

* All shores of the earth considered, are progradation and retrogradation equal? Or *must* one exceed the other?

You already have the clue. The rugged, deeply indented shore line which we first studied we called "drowned"; at least we called its bays drowned valleys. Either a rise in sea level or a subsidence of the land has produced partial submergence of a stream-carved topography, interrupting the cycle in maturity. At present we are not concerned in determining which moved, the sea or the land. We'll consider it as a movement of the land and we'll say "subsidence" or "submergence."

Then we gave attention to shore lines marked by far-flung fairly straight barrier beaches, separating low monotonous coastal plains from shallow seas offshore. The land surface and the sea floor are really one continuous plain, partly out of water, partly submerged. For the origin of such a shore line, we think immediately of two possibilities. Either (1) the plain is an old wave-cut platform now uplifted to be partly out of water, or (2) the plain surface is due to deposition, having once been entirely submerged and aggraded to smoothness beneath the shallow sea, and now partially uplifted. In both cases we ask for uplift, instead of the subsidence the rugged irregular coast demanded. These then are the two most common types of initial shores: shore lines of submergence where the land went down or the sea level rose, and shore line of emergence where the land rose or the sea lowered.

In the subsequent modifications of initial shore lines, sea cliffs and spits should be far more common on the shore lines of submergence, for ample opportunities for their making are afforded there. Barrier beaches should be restricted to shore lines of emergence. But can we safely generalize and say that the modifications of one type are retrogradational, of the other progradational?

The shore line of submergence shows both destruction of land, and construction; but destruction (retrogradation) is dominant as far as we traced the changes. The shore line of emergence, where marked by barrier beaches, is dominantly constructional (progradational). If we make the generalization, it obviously must not be too sweeping.

THE MARINE CYCLE OF EROSION. Another question! Can we generalize on the work of shore agencies and say that a "cycle" of erosional changes occurs, with youthful, mature, and old coast lines marking its stages? Our greatest authorities on shore processes and shore-line development believe so and one of them devotes one hundred and twenty-five pages of his textbook to a persuasive setting forth of the evidence. Though you now possess only very limited information about shores, we can profitably sketch through the argument as applied to shore lines of submergence. Remember, the concept of a cycle of shore-line development is no more based on actual observation of the full gamut of changes than is that other concept, the cycle of stream-valley development. The sequence in both is inferential.

Here is a shore line of submergence we call very young—because it is so little altered from what an initial shore line of submergence should be. We say that another shore line is in late youth—because its sea cliffs are higher and its wave-cut platforms wider, its spits longer, its bays more nearly closed off, its headlands more extensively eroded back. Higher and wider—larger—more nearly closed off—more extensively eroded back . . . than *what?* * Than they would be if less had happened to them. That's our inference, based on what we see happening along shores. If you won't accept it, you have two alternatives. (1) Processes other than shore agencies made the shore lines. (2) The shore lines were created the way they now are and have not changed since.

In our consideration of the changes wrought by waves and currents on a shore line of submergence, we went no further than the cliffing of headlands and the consequent building of spits and bay bars, enclosing of lagoons, perhaps the growth of deltas. Did you think that was the end of the attack? Only one thing in our picture suggested it; the increasing width of the wave-cut platform. It is obvious that increasing expanse

* Something like reading advertisements for dentifrices or new cars, isn't it?

of shallow water offshore means greater damping down of the incoming waves, a reduction of the vigor of attack.

Granted—but is it a permanent protection? Wave drag on the platform is ceaselessly shifting abrasive materials back and forth, ceaselessly grinding down the platform on which once stood the initial headland, ceaselessly carrying off the finer products of the mill into deeper water. The platform isn't level. It has a gentle offshore slope, which the grinding-down process constantly moves nearer the land as the cliffs retreat and the headland shortens (Fig. 101).

What of the bays while this goes on? They must shorten also. Spits and bay bars are temporary things, composed of loose material, as transitory as alluvial fans and channel sand bars in stream work. As the bays that gave them shelter disappear, they must go. The shore line's irregularities now decrease and a time is near at hand, barring interruptions, when waves and shore currents will have reduced to "powder" the rock of the peninsulas, will have carried the detritus away, will have wiped out the original irregularities and made a straight shore line, the shore line of maturity.

There's an unjustified assumption in our argument that the highly irregular initial shore line is destined to become straight. We said that peninsular extremities were more exposed than the bay shores. That is correct. We said they would therefore suffer more from erosion. Correct, also. But on this infinitely varied earth of ours, will every initial shore line of submergence margin a coastal land of uniformly resistant rock? Suppose that the old stream-eroded topography, which later became partly submerged, were dissected out of an Appalachian type of structure. The ridges (they would make the peninsulas, wouldn't they?) are of harder strata, the valleys (bays) mark belts of weaker rock. There's a statement of proportions or ratios needed here. The cliffs will retreat, the peninsulas become shorter, the heads of bays less protected, until the rate of erosion is the *same* on every kind of rock along the coast. But it won't be a straight coast.

If maturity of a shore line is, as the authorities contend, a nearly perfect adjustment between shore-line form and the

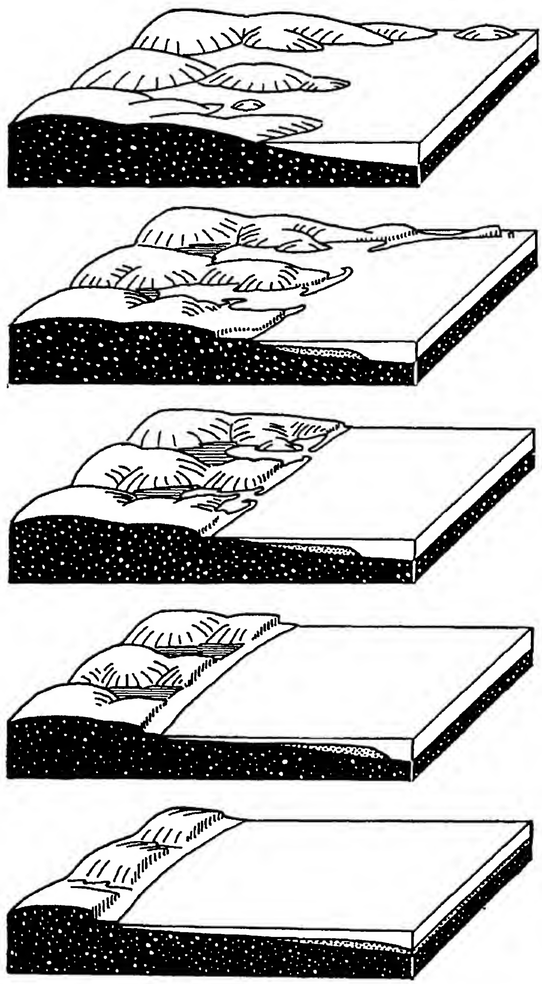


FIG. 101. The Marine Cycle of Erosion on a Shore Line of Submergence.

Identify (1) cliffed headlands, (2) spits, (3) wave-cut and wave-built terraces, (4) marsh and delta deposits. The bays on this coast were not large enough, apparently, to develop bay-bars and spits curving back into them. (After James, *An Outline of Geography,* Ginn and Co., 1935.)

attack of shore processes, what further changes may be conceived of as leading to and characterising old age? In answer-

ing this question we must first realize that we have so far asked of *streams* only that they set the stage with a rugged mature topography of ridges and valleys. Then, except for deltas back of bay bars, we have ignored them and their work. Is that fair?

So far as our argument has gone, it is fair enough. At the time of the submergence the major valleys became drowned as far back as the bays extended, and stream work in them stopped. Still farther back, the rivers simply continued their leisurely widening of valleys already mature. This would make no difference with the work of shore processes—until the shore line, if ever, becomes retrograded farther inland than the bay heads. And you need only note the "hanging" valleys of minor (therefore younger) streams which reach the shore without joining a major stream, shown in Fig. 97, to find further defense for our neglect. They testify convincingly that retrogradation, before maturity is reached, is more rapid than degradation. It seems safe, therefore, to conclude that until a shore line of submergence has reached maturity the concomitant work of streams on the coastal land is not a factor in the problem.

After straightening has proceeded until the rate of retrogradation is the same everywhere, the shore line will be driven back at a fairly uniform rate. As it retreats, new positions will be approximately parallel with older ones. There is now a broader wave-cut offshore platform than ever before. Its effect on wave attack, we have already considered. Cliffs can be driven farther back only as this shoal-water platform is ground down and planed off to allow unimpeded wave passage across it; a long slow process which must become ever slower as the platform widens. As the rate of cliff retreat diminishes, the hanging minor valleys succeed in obtaining a uniform gradient, the cliff faces suffer more from weathering and slope wash, become gentler, soil-covered, vegetation-covered, more like the upland slopes back from the sea. Though the rate of running water erosion is also decreasing (the time is now late maturity or early old age), it is probably as rapid, relatively, as the shore-line changes.

The peneplain of the cycle of stream erosion is beginning to be foreshadowed in the greatly lowered divides and the greatly widened valleys. Sea cliffs have ceased to be high, have ceased to be cliffs. And, offshore, under the waves, another peneplain is in the making, the peneplain of marine abrasion. In old age of both cycles, the erosional plain on the land blends with the erosional plane under the water. The shore line is very simple, almost featureless.

SUMMARY OF SHORE CHANGES. On an irregular coastal land, whose initial shore line is due to submergence, progradation is only a temporary phase of the adjustments demanded by the shore agencies. Retrogradation exceeds it from the start and eventually completely dominates. There is no need for cooperative stream erosion; waves and currents are competent to do the work unaided.

In the early adjustments on a shore line of emergence, progradation may dominate everywhere. But the never-ending loss of sediment from the agitated shore zone to deeper water allows waves to reach the object of their attack and retrogradation must eventually become dominant.

This is theory. There are no truly old shore lines existing today, just as there are no peneplains whose base level is present sea level, though both marine and fluvial cycles seem to be justified concepts. Given time enough and no interruptions by other processes, the shore agencies of waves and currents seem adequate to the task of destroying the land of the globe. The last vestige of North America falling victim to the attacking waves, the Atlantic and Pacific mingling across the continent's truncated stump; this appears a bit fantastic. But note again the qualifications; time enough, no interruptions. We said almost the same thing about running water and ground water; we shall repeat it for the work of the wind. The earth certainly has a youthful countenance for one so old and so beset by gradational agents. Are there rejuvenating processes? Or are we all wrong in our conclusions about the fate of land?

BIBLIOGRAPHY

Agar, W. M., Flint, R. F., and Longwell, C. R., *Geology from Original Sources,* Chapter VII, Henry Holt and Company, New York, 1929.

Allen, V. T., *This Earth of Ours,* Chapter VI, Bruce Publishing Company, Milwaukee, 1939.

Croneis, C., and Krumbein, W. C., *Down to Earth*, Chapter 12 University of Chicago Press, Chicago, 1936.

Hobbs, W. H., *Earth Features and Their Meanings*, Chapter XVIII, The Macmillan Company, New York, 1931.

Lobeck, A. K., *Geomorphology*, Chapter X, McGraw-Hill Book Co., Inc., New York, 1939.

Longwell, C. R., Knopf, A., and Flint, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology,* Chapter 10.

Loomis, F. B., *Physiography of the United States,* Chapter V, Doubleday, Doran and Company, Garden City, 1937.

CHAPTER XI

GRADATION BY THE WIND

Ability to carry debris. If streams and shore currents (density of 1) can pick up rock particles (average density of 2.5) only when markedly turbulent, it would seem that wind (density at sea level only about 1/800 that of water) must be essentially impotent as a transporting agent. If a certain stream velocity is required to roll certain sized particles along the bottom, how much greater velocity wind must have to move the same particles! Your answer probably is that wind will transport (carry or roll) detritus only if the particles are very light. Just what do you mean? Of course dust particles weigh less than sand grains, but is the specific gravity of their material any less? The powder made from a cubic inch of solid talc weighs as much as the original piece, yet falls slowly through air, is easily transported by wind. The material hasn't been made any lighter by crushing or grinding. But the total surface area of the cubic inch has been vastly increased.*

Now that you have caught the idea, let's add a closely associated idea; that a far greater volume of air than of water is required to carry any given load, no matter how fine the particles. In other words, whatever the velocity and turbulence of the wind, a cubic foot of dusty air can never contain the detritus a cubic foot of turbulent muddy water holds. Air hasn't the density necessary to support the load. One geologist estimates the capacity per cubic unit of air as one ten-thousandth of that of stream water.

Against these limitations of wind as a transporting agent, are there any items in its favor? Put it this way: wind blows

* Then what did you mean by "lighter"? It's another statement of ratios.

across the Mississippi drainage area just as water flows across it. What are the relative depths and widths (volumes) of the air currents compared with the water currents? Here winds rank far, far ahead of streams. Our geologist estimates that if a cubic foot of air *could* transport as much fine material as a cubic foot of water, the Mississippi Valley winds could carry away ten million times as much sediment as the river does.

Each cubic unit of air only one ten-thousandth as effective as stream water, but ten million times as much air as water flowing off the Mississippi drainage area! The astonishing conclusion is that winds can transport a thousand times as much dust out of such a region as can the streams!

Do they? There's another factor in the problem. A mile-long freight train, each car with a fifty-ton capacity, may be made up of "empties." Capacity to transport is one thing; getting the air loaded for the trip is another.

LOADING. Wind does but little in preparing material for transportation. Almost all the reduction of debris to sufficiently minute particles is done by other agents. Then, if the wind finds them dry and loose,* picking up is a matter of friction.† Weathering makes most of the *fines* which winds blow away. An arid region loses more to the wind than does a humid region during a drought because, for one thing, there is little or no protective vegetation.‡

That wind varies in velocity from time to time is as well known as that water always runs downhill. There are no comparable velocity variations among rivers or glaciers or in ground-water circulation.§ Though light winds will carry dust, strong winds are required to pick it up in considerable quantity, to load the air to the proportions of a dust storm Once taken up, very fine dust may remain suspended by faint

* Hard dry mud, for example, isn't going to be blown away very rapidly, is it?

† Friction between air with sufficiently high velocity and particles of sufficiently large —————— in proportion to their ————.

‡ What's another good reason?

§ Should we add waves and shore currents?

convection currents even in what we would call a complete calm. Hence the air, at least in the troposphere, is never perfectly free from dust.

Sand grains and even small pebbles may roll, skid, or hop-skip-jump under the urge of vigorous gusts but they promptly come to rest when the gust dies away. The high variability in wind velocities and the prompt deposition of coarser detritus from any slackening make of wind a highly selective transporting agent.*

S o r t i n g . Given: a loamy soil where weathering (which does no sorting) has produced a mixture of sand and clay particles. Will a gentle wind, able to carry dust but not sand, blow all the dust away and leave only sand? Your answer is correct—only the very surface will lose any dust; most of it is inaccessible to the wind. Will a strong wind carry both dust and sand away? If so (it is so), that isn't sorting, is it? Picking up or loading involves sorting only at the lowest velocities and therefore only among the finest materials. It is when strong winds die down that the gradual dropping out of progressively finer particles occurs, farther and farther from the source.

L o e s s . Does dust settle from the air, out of doors, remain, and accumulate in sufficient amount to constitute a geological deposit? It may sound a little improbable to hear that there are such deposits tens, even hundreds, of feet thick and covering hundreds of thousands of square miles. *Loess,* the geologists say, is the dust of uncounted centuries, blown to the region from some adequate source (an extensive arid desert would be most probable), dropped there, some doubtless picked up again but some trapped in a cover of vegetation and so remaining and accumulating. Loess is an unstratified deposit, texturally finer than sand but coarser than clay, a mantle rock without roots, hence a product of some transporting agent. There are two great loess-covered regions in the United States, one on the Columbia Plateau in contiguous parts of Oregon, Washington,

* The very antithesis of which picks up all sizes without discrimination, carries and deposits all sizes without sorting.

and Idaho, the other and larger one along the Mississippi River and its tributaries from Wisconsin to Louisiana and reaching west to Nebraska and Kansas. Iowa is very largely loess-covered, Iowa's agricultural pre-eminence owes much to the fertility of soils in loess. In both regions, loess is being eroded away by streams today. In both, the deposit therefore records a former drier climate just as the glacial drift of the northern states records a former colder climate.

A new term, the Dust Bowl, was on almost everybody's tongue, in this country, a few years ago. It wasn't a bowl.

FIG. 102. The Black Blizzard, the Dust Storm of April 14, 1935, near Lamar, Colorado. (J. H. Ward, Lamar, Colorado.)

It was that region in the Great Plains where dust storm after dust storm was making life wretched in town and country alike, where the topsoil was being literally blown away, where (Fig. 102) many thousands of square miles of fertile prairie were all but ruined through denudation by the wind, where thousands of farms were abandoned outright, and many towns nearly so, where the Federal Government had to resettle thousands of farmers in other regions. In the Dust Bowl at times one could not see half way across a street. In diminishing intensity, dust was detectible as a yellowish haze down along the prevailing westerlies as far as the Great Lakes and the Atlantic

seaboard. Mud rains * spotted windows and windshields in the northern and eastern states. Rain brought most of this dust to earth again before it reached the Atlantic seaboard.

Ignorance of what the wind could do under favorable conditions was the fundamental cause of the Dust Bowl calamity. Nature supplied one of the conditions; a cycle of dry years. Man had already done his part; the destruction of the protecting prairie sod, the annual plowing of naked soil for cotton and for corn. No one who read current events in 1935 can question

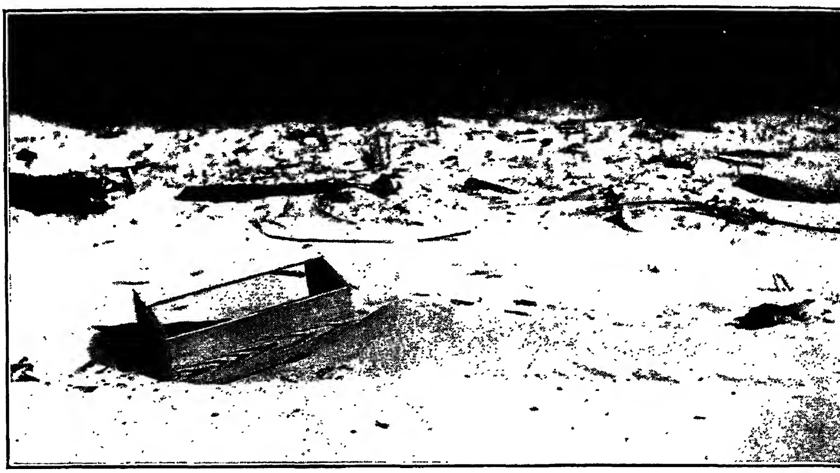


Fig. 103. Initial Lodgment of Sand on Both Windward (Left) and Lee (Right) Sides of an Obstacle.

Why has any sand stopped on the windward side? (E. S. Bastin, Photograph.)

the capacity of the air for transportation of dust or the geologist's interpretation of the origin of the Mississippi Valley loess.

Dunes. Sand is about the coarsest material that wind will transport and only in whirlwind convection currents is it ever lifted more than a few feet off the ground. Commonly it travels either by rolling or by a series of leaps and landings, timed with the gustiness of the wind. Obstacles on the ground

* Dust from Texas, Oklahoma, Kansas, Colorado, plus water from the Gulf of Mexico that refused to come down as it crossed the region so sorely in need of it.

cause eddies and deflections in the wind and decrease its velocity. They therefore cause deposition, chiefly in their lee. Mounds and hillocks of sand are thus formed (Fig. 103) and, growing larger, become obstacles in their own right, especially if soil moisture * and some vegetation come to their aid. Under favorable conditions, dunes may grow to be more than a hundred feet high.

Dune shapes are varied but, while growing, they possess one characteristic in common, a relatively gentle windward

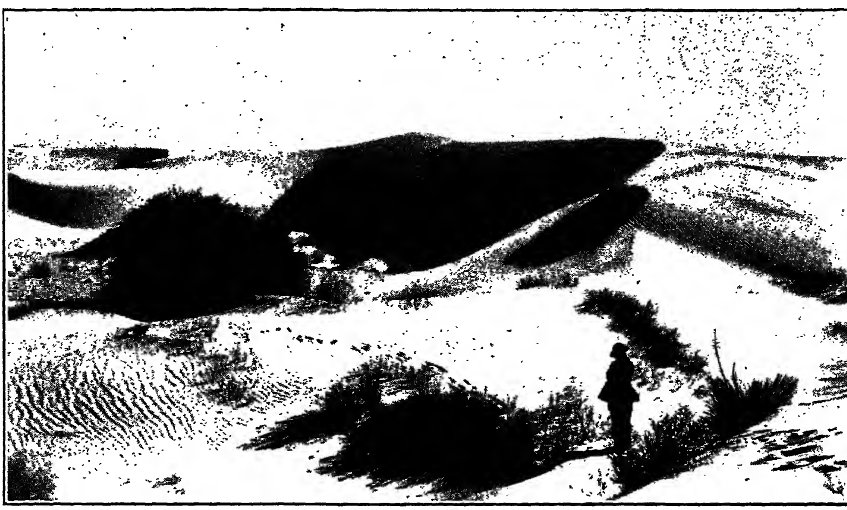


FIG. 104. Sand Dunes.

Wind direction from left to right, or vice versa? (From Cleland's *Geology, Physical and Historical,* Copyright. By permission of American Book Co., Publishers.)

slope and a lee slope as steep as loose sand can lie (Fig. 104). Sand grains arriving to join the dune aggregate travel up the windward slope, roll or leap off the crest into the protected lee. Constant addition at the top of this slope maintains the steepness, keeps the sand at the sliding angle.†

A peculiar feature, born of this method of growth, is that

* Wet sand won't blow.

† Students climbing a dune's lee slope almost invariably announce that, for every step up, they slide back two.

dunes "march." Their growing lee slopes advance, burying farmland, forests, roads, even villages. If the advance of the lee side is being made at the expense of sand eroded off the windward side, then the dune form moves on, and buried trees and buildings may come to light again. But if sufficient sand is continually brought to the dune (on-shore winds across a sandy beach would qualify), the energy of the wind may all be consumed in transportation and no erosion will occur. Such

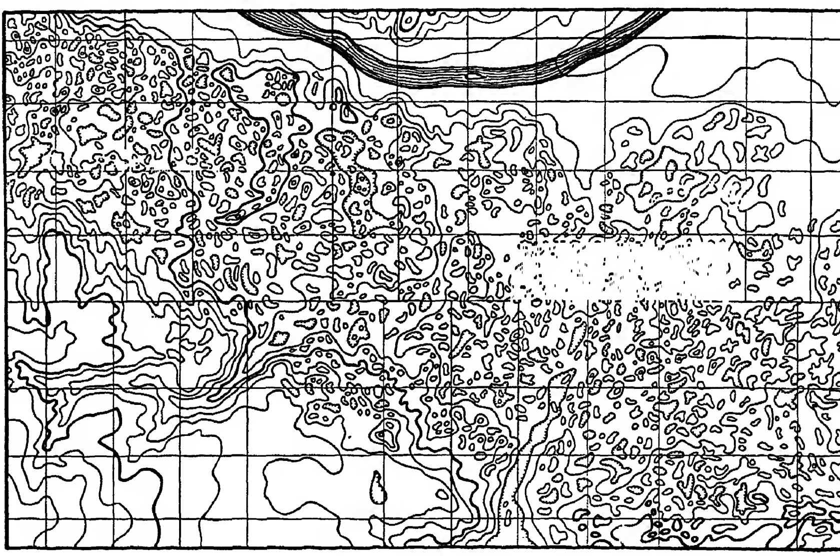


FIG. 105. Contour Map of Dune-Covered Region in Kansas.

The map is ruled to show square miles. Undrained depressions are almost as numerous as dunes. How do you explain the origin of the depressions? (After Salisbury and Atwood, "The Interpretation of Topographic Maps," Professional Paper 60, U. S. Geological Survey, 1908.)

dunes simply grow larger, their lee advances, but they don't march across country.

Though aridity of a region favors dune growth, it does not guarantee it. There must also be enough sand from weathering of the local rock. Furthermore, enough sand may be provided, in a humid climate, for dune growth. On lake and ocean shores and on river floodplains, sand may drift during intervals of dry weather and dunes may be built.

The topographic aspect of a dune-covered region (Fig. 105) resembles in some ways that of a region covered by moraines, especially the broad moraines left by continental ice sheets, also a region riddled by sink holes. Hills are short and irregularly shaped and distributed. Closed depressions are numerous among the hills of piled-up sand. A dune topography is as clearly constructional as a moraine topography. The hills are great dump piles, quite unlike in shape and ground plan the linear divides left between stream valleys or the hogback ridges between outcrops of weaker rock layers.

Checking wind erosion of soil. Wind may blow away the arid region's finer products of weathering as fast as they are formed and nobody cares very much. When it starts a Dust Bowl, however, and ruins fertile farming land, we do care. The Soil Conservation Service has studied and experimented with two types of preventive measures, vegetative and mechanical, and recognizes that with variations in local conditions various methods must be used. Cover crops of grass (Bermuda grass, Colorado grass, even crab grass), of alfalfa and cowpeas, are substituted for or rotated with ordinary crops. Stubble is cut high and left without fall plowing; straw, stalks, and manure are spread over the fields as protection against the winter winds; windbreaks of trees are recommended. Fall plowing in many soils simply invites blowing of the soil; rolling of the soil is detrimental; any cultivation that fines the soil is to be avoided. Plowing so that the soil is strongly ridged across prevailing winds is advocated. Turning under of almost any organic trash increases the humus content and thus reduces blowing. When farmers understand that they were part of the cause of the Dust Bowl calamity, and cooperate with the Soil Conservation Service, much future damage will be prevented. Nature's cycles of dry years will recur, however, and return of much of the region to grazing land, whose sod is never broken, is the only sure remedy.

Checking dune migration. Disasters from migrating wind-driven sand do not figure in newspaper ac-

counts as do floods and dust bowls. Like slope wash, the process is slow and the annual losses are accepted and adjustments made. They can be prevented, however, if economically desirable. The enemy must be flanked and attacked from behind. His supply train must be cut. Nothing but a battery of power shovels can win by fighting the advancing front.

There is enough soil water in humid-climate dunes to support many types of sand-binding plants. They must be set out on the windward side, to hold what sand is there and what may be added. Gravel or cinders scattered over the bare sand may be a feasible method. Spraying the windward slope with crude oil, which effectively stops that sand from traveling, is used chiefly by railroads whose right-of-way is being transgressed. A fundamental principle of the problem is that sand travels only close to the ground. Sufficient reduction of wind velocity at this level can be secured by fences, lines of cut brush, and rows of sand-tolerating shrubs across the wind. In coastal humid lands, numerous former wastes of wind-drifted sand have been transformed into income-producing pine forest land.

Wind erosion of bedrock. If you have ever walked across an active dune on a windy day, you haven't yet forgotten the sting of the sand against your face and hands. If you have ever picked up a bottle lying for a year or so on a wind-swept dune slope, you perhaps remember that its exposed upper part had no luster or transparency, had a fine-textured ground-glass surface. That's the work of the natural sand blast. Exposed rocks are abraded in much the same fashion and are likely to show cumulative results of centuries of the experience. An etched pattern usually develops, harder crystals, nodules, and thin layers being left in relief and the depressions possessing characteristic elongated concave facets, comparable to the marks of mice teeth on hard cheese (Fig. 106). A rock sufficiently hard and dense and swept by sufficiently fine sand may actually be polished, show no matte or ground-glass surface. Wind abrasion in arid regions is undoubtedly an important method of rock destruction. The wind must have tools,

of course, and sand is most effective. What it removes is probably mostly dust-sized particles.

DEFLATION. Geologists used the word before economists discovered it, and in a less figurative way. *Deflation* is regional degradation by the wind. It is an inference, simply because our observations on wind erosion and transportation cover so limited a span of time. We see the work going on where there is a paucity of soil moisture and vegetation. We find in such regions abundant evidence of abrasive wind work

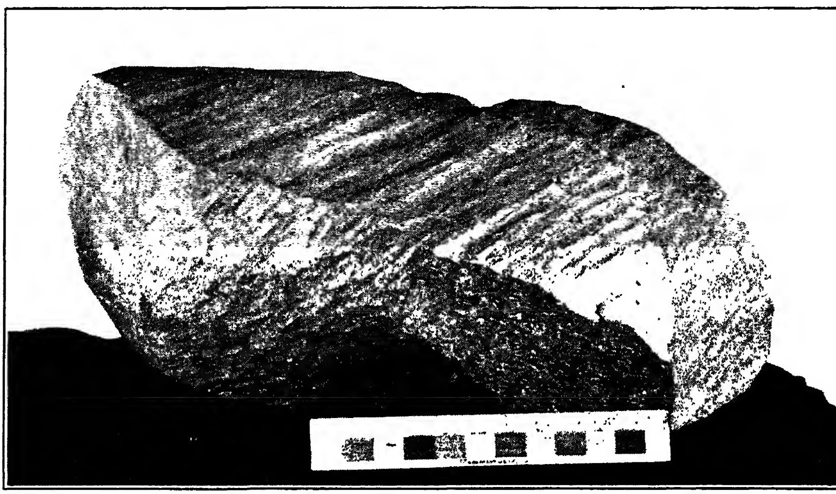


FIG. 106. Work of Nature's Sand Blast.

A boulder of granite from the slopes of Pikes Peak, Colorado. Apparently the boulder changed its position during the experience.

on exposed rock. We discover that there are broad closed basins in weaker rock, clearly the work of an agent that can lift material out of these depressions. So we say deflation. Our theory requires that weathering and wind abrasion reduce the rock essentially to dust before it can be blown away. Time enough must be granted, and freedom from interruption.

No peneplanation by the wind alone is asked for; there's usually too much rain in the most arid climate. Even if uninterrupted long enough, wind is so sensitive to degrees of rock resistance and so little in need of a descending land surface to

flow over that no smooth old-land would be probable. We do think, however, that if the earth had no hydrosphere—therefore no running water and its work, no ground water and its work, no glacial work, no shore lines and their changes—there still would be reduction of highlands and filling up of lowlands, the final result of which would be a fairly even surface of the lithosphere.

SUMMARY. The extent to which wind makes contact with land is unrivaled by any other gradational agent. The opportunity for erosion and transportation is conditioned by, first, an adequate wind velocity and, second, a dry and only sparsely vegetated surface. Wind produces only a small part of the detritus it carries; it must wait on weathering for most of its load. The low density of air results in definite limitations to size of particles carried. Winds are essentially horizontal currents, rarely conditioned or directed by topography beneath them. Hence transportation is not limited to down-slope directions. The load may travel uphill, it may be picked up at the coast and travel back inland. Deposition of dust is favored by entrance into a more humid region, of sand by local decreases in velocity of the bottom air. Dust or sand may be blown, deposited, blown on again, deposited again, the cycle continuing almost indefinitely on the land. But where blown well off the land, the first deposition is the last; it is a total loss to the lands, a permanent addition to oceanic sediments. Given enough time and no interference, the winds of the earth could destroy the lands.

BIBLIOGRAPHY

CRONEIS, C., and KRUMBEIN, W. C., *Down to Earth*, Chapter 6, University of Chicago Press, 1936.

LOBECK, A. K., *Geomorphology*, Chapter XI, McGraw-Hill Book Co., Inc., New York, 1939.

LONGWELL, C. R., KNOPF, A., and FLINT, R. F., *Textbook of Geology*, John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology*, Chapter 9.

LOOMIS, F. B., *[illegible] of the United States*, Chapter II, Doubleday, Doran and Company, Garden City, 1937.

CHAPTER XII

DIASTROPHISM

EARTHQUAKES. Our discussion of the work of each gradational agent has ended with a warning about interruptions. Tacitly, if not avowedly, we have been accepting movement *in* the lithosphere as the villain in the piece. Rejuvenation of streams, new cycles of erosion, drowning of coastal lands, tilting of stratified rocks; apparently nothing but diastrophism could cause these things. Let's now consider present-day manifestations of the earth's internal energy, events over which the sun and air and water and ice have no control.

Not more than a month ago, some earthquake made the front page of the daily paper, was noted by radio news commentators. Earthquakes are even more frequent than that! The seismologists say in all seriousness that the earth is trembling somewhere all the time, minor tremblings but significant. They take their information from the seismograph, a source more sensitive to earth tremors than rattling windows, or falling chinaware, pictures, and chimneys. They often know of major quakes before radio, cable, or telegraph can carry the news—know where the quake occurred, when it occurred, approximately how vigorous it was. It won't be long before they will know enough about some quake-ridden regions to begin forecasting!

Cause. Earthquakes travel from the place of their origin out in all directions as a series of decreasing waves * in the solid earth. Most earthquakes originate from sudden fracturing deep down in the bedrock where growing stresses finally exceed the strength of the rock. Some of these fractures come to the

* Remember, there are sound waves and light waves. Not all waves are like those on the surface of water.

surface, a few having lengths of a hundred miles or more. They are *faults,* offset dislocations in the rock along fairly plane surfaces (Fig. 107), commonly at high angles with the horizontal. The rock has slipped down on one side or has been pushed up on the other, both sides remaining tightly together. Some regions have many faults, yet no earthquakes of local origin. They are dead faults, scars left by former movements that undoubtedly did cause earthquakes. In such regions, stresses have ceased to accumulate, movement has ceased, and quakes therefore no longer occur.

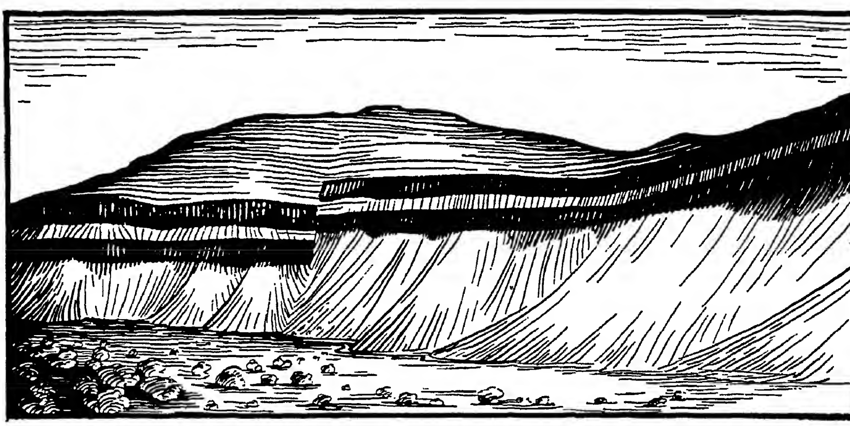


FIG. 107. Fault in Sedimentary Rocks in Western Colorado.

The displacement shown is about 150 feet. (After "Book Cliffs Coal Field . . ," U. S. Geological Survey Bull. 851, 1934.)

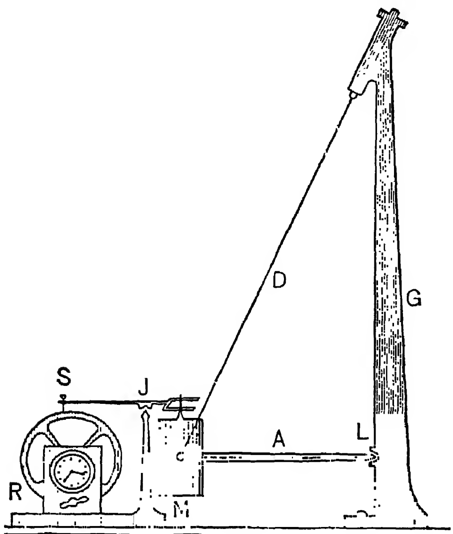
Nature. The amount of dislocation in a destructive earthquake may be only a few inches. Nature's regimen isn't much disturbed by the rapid to-and-fro shaking of small amplitude, nor would ours be if we, like our ancestors, lived in skin tents, cooked over camp fires, waded rivers. Destruction is wreaked on our buildings, gas and water mains, bridges, towers, dams; death comes in collapse of masonry structures, in fires in the wreckage after the water mains are broken, in epidemics among survivors from polluted water. Destruction of buildings is most severe on "made land." Steel frame buildings founded on solid rock are fairly immune to earthquake damage.

The really dangerous place out of doors and out of streets is the seacoast. Whether the faulting occurs beneath the ocean or the land, very broad water waves are likely to be made by the shock. These waves spread like those made when a pebble is thrown into still water. Enormous damage is sometimes done in seaport cities by these so-called "tidal" waves.

Seismic regions. There are certain linear tracts of the earth's surface, generally close to and parallel with continental margins, where earthquakes originate with especial frequency and may be especially severe. Examples are California and Mexico on the west side of North America, almost the entire west coast of South America, the islands of Japan and the Philippines along the west side of the Pacific, Java and Sumatra along the east side of the Indian Ocean, parts of India, Asia Minor, and the northern border of the Mediterranean. These regions significantly include also many active volcanoes and erosionally youthful mountains. They are being selected, for some reason, as sites for these manifestations of internal energy.

The seismograph. The principle of the instrument which has made a science of seismology possible is simple, though the mechanism is delicate and complicated. Suppose we hang an iron ball a foot in diameter by a steel wire from a high ceiling. It is a pendulum, free to swing in any direction. Projecting down from the under side of the ball is a point just touching the floor. The floor is covered with loose, dry sand an inch deep. Now ensues an earthquake. The floor of the room is moved with the vibrations of the earth, the ball is not! Its inertia holds it stationary in space while the horizontal oscillations of the quake move the floor back and forth beneath. The point projecting down in the sand draws lines indicating the direction and amount of movement in the shock. We have constructed a crude seismograph. We measure the speed of an automobile, the velocity of a bullet, almost any movement of a terrestrial object, by referring to the earth's surface as stationary, but here we must measure movements of the earth's surface by referring to a steady point affected as little as possible by the earthquake vibrations. Three components are generally meas-

ured, north-south, east-west, and up-down. Horizontal pendulums are preferred (Fig. 108), a beam of light on photographic paper eliminates the friction of a marking point of any kind, anchorage on a bedrock foundation eliminates the vibrations and jars of the building itself, unvarying temperature of the instrument is a prerequisite to accurate measurements.



After Sieberg.

Fig. 108. Diagrammatic Representation of a Seismograph.

The upright post (*G*) and the recording device (*R, J*) are attached firmly to a pier mounted on bedrock. The heavy weight (above *M*) is connected with the post (*G*) only by a freely moving joint (*L*) and a flexible wire (*D*). Records are made by the stylus (*S, J*) on a revolving drum (*R*), which is driven by clockwork. (Longwell, Knopf and Flint, *Outlines of Physical Geology,* John Wiley and Sons, 1934.)

The seismogram. The seismograph record is drawn on a rotating cylindrical drum around which the photographic paper is wrapped. The clock-driven drum rotates, let's say, once an hour. Since its axle is screw-threaded, it is moved endwise a little with each rotation. Thus the record for a day consists of a long spiral track winding twenty-four times around the drum. The paper, when removed and developed, has twenty-four straight parallel lines, provided no shock has affected the instrument. One minute intervals may be marked off on these lines by a device interrupting the beam of light every sixtieth second.

But if earthquake vibrations pass through the bedrock, the pendulum arm with its beam-of-light pointer is thrown into oscillations and the line drawn reveals the direction and distance to the earthquake source and the magnitude of the quake.

A distant quake will be recorded by at least three different kinds of oscillations of the recording beam, occurring in sequence. Thus, there are three kinds of waves or vibrations sent out through the earth body, which arrive at three different times and therefore travel at three different velocities. The first two of these make short oscillations of the pointer, are known as the preliminary waves P(rimary) and S(econdary). The third set of waves to arrive throw the pointer into long swings (L(ong) waves), in which the further record of P and S waves is lost.

Suppose the fault or slip in the rock occurred fifteen miles below the surface. P and S waves spread out in all directions, along fairly direct routes. Those coming to the surface give rise to L waves which proceed to spread out in ever-increasing circles like the water waves around the pebble. P waves are compression-rarefaction waves, similar to sound waves. They travel approximately six miles a second. S waves may be compared with light waves in that the direction of vibration is transverse to the direction of travel. Their velocity is about four miles per second. L waves are more like water waves, in which the vibrating particles travel in orbits. They spread out on the surface at about two miles per second.

An earthquake occurred in Chile, January 25, 1939, 5480 miles (measured on the curve of the earth) from the Uni-

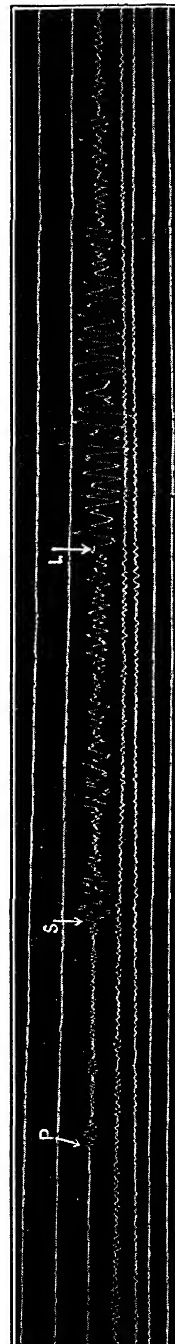


FIG. 109. Seismogram of the Chilean Earthquake of January 25, 1939. Record of the north-south component of the United States Weather Bureau Observatory's seismograph at the University of Chicago. This earthquake cost 30,000 human lives. (U. S. Weather Bureau.)

versity of Chicago seismograph station. Along the chord of that arc distance, the P waves outran the S waves by 12 minutes and 4 seconds and the L waves, coming along the arc, were 15 minutes and 53 seconds behind the S waves in arriving. Had the quake occurred just across the state line, in Indiana or Wisconsin, the waves would all have arrived at so nearly the same time that this sorting out would not have occurred (Fig. 109). But all we knew from our own pendulum record at Chicago was that the quake was 5480 miles distant, in one of two possible directions. Cooperation with at least two other seismograph stations, several hundred miles distant from us and from each other, was necessary for definite location of the quake source.* By that time, cable news had arrived.

The interior of the earth. One of the most significant things learned from seismograms is that P and S waves do not travel in straight lines. Some seismologists speak of them as "rays" instead of waves, and that word gives us the clue, for the direction of earthquake wave propagation undergoes both refraction and reflection. More and larger deflections occur if the waves have to pass more deeply through the earth between source and station.

This can mean only one thing, the same thing that makes the stick thrust diagonally into water look bent at the water line. The "rays" at different depths pass across boundaries of different densities of earth stuff, or are reflected from those boundaries. The earth body must be made up of different shells, increasing in density toward the center. A generalized interpretation calls for two shells and a core. The outer shell, about seven hundred miles thick, may be called the lithosphere since waves travel through it with the speed they have in average rock. High angle rays refract as they go deeper than this, low angle rays at this depth are reflected (return to the surface with angle of incidence and reflection equal) (Fig. 110). A

* Try this problem. The sorting out of the three waves of a particular earthquake shows that it was 1600 miles from the Washington, D. C., seismograph station, 2050 miles from the St. Louis station, and 3675 miles from San Francisco. How would you determine where it occurred?

thousand miles farther down is another "discontinuity" or refracting-reflecting boundary, the outer surface of the "core" whose density is certainly equal to that of metallic iron (specific gravity 7.87). Curiously, the S waves either fail to traverse the core or get through in greatly weakened condition.

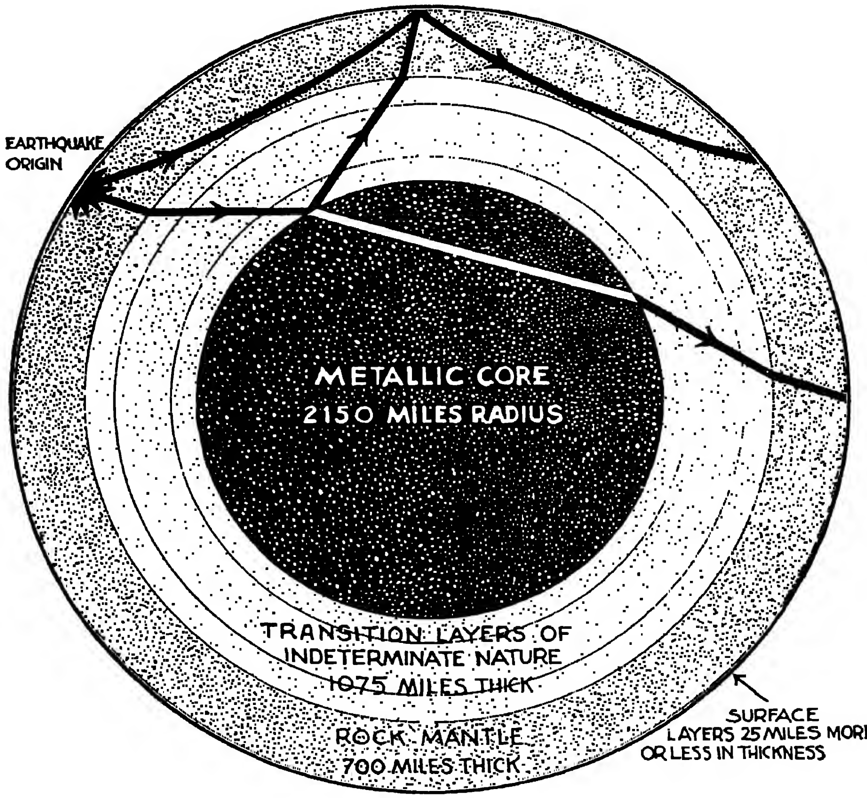


FIG. 110. Representative Courses Followed by P and S Waves.

Both refraction and reflection are shown. A curious situation exists at the top of the diagram. What's your explanation for it? (N. H. Heck, *Earthquakes*, Princeton University Press, 1936.)

Some think this means that the core is liquid. If it is, that liquid isn't ordinary lava or magma, whose specific gravity is about 2.6.

To realize how much we have learned about the earth's interior and the nature of earthquakes since highly sensitive seismographs have been constructed, one has only to compare a

modern book on seismology with one written twenty years ago. Today's seismologist is an explorer in a newly discovered world. He may have all the thrills any Columbus or Magellan ever had. The latest discovery is that of deep-focus earthquakes, originating four hundred miles below the surface. Once geologists believed the earth surely to be molten at such depths "below the crust" and rather recently they thought the enormous pressures so far exceeded strength of rock that stresses would be relieved as fast as developed. Hence no abrupt failure (faulting) could be possible at any considerable depth in the body of the earth. Perhaps it isn't faulting that causes the deep-focus earthquakes, perhaps "chemical explosions" or some other changes unlike anything we know at the surface are the causes.

If the earth is layered, as the P and S waves clearly prove, there must be a reason for it. The earth was "made that way" of course, but we are curious to know *how.* We don't yet. Nor did men once know what caused the tides, or the moonrise, or the stratification of rocks, or the bedrock striations of Canada and northern United States. It is still a very interesting earth.

MOUNTAINS AND CONTINENTS. Earthquakes are phenomena of present-day diastrophism, testimony that the earth body hasn't yet settled down to the serene calm of old age. Dead faults and folded strata are records of past diastrophism. So far as we can read that record, present diastrophic activity is about as great as any in the millions of years gone by.

Mountain ranges. The most conspicuous consequences of diastrophism are mountain ranges. Their indurated rock commonly contains stratified sediments, with fossil marine clams, snails, corals, indeed all the wealth of sea life represented in rocky summits of the great mountains of the earth. Both faulting and folding have made their uplift possible, uplift from the bottom of shallow seas to dizzy heights in the troposphere.

The idea that mountain ranges have been made by vertically

acting forces is too far from harmony with mountain structures and mountain patterns. The well-known folded strata of the Appalachians, if leveled out again, would make a belt nearly fifty miles wider than the mountains now are. There was fifty miles of east-west shortening (or narrowing) of North America when the Appalachians were made. Many other folded mountain ranges tell the same story: lateral squeezing was the primary direction of movement, the mountain uplift was only a consequence of that. As though a pile of blankets

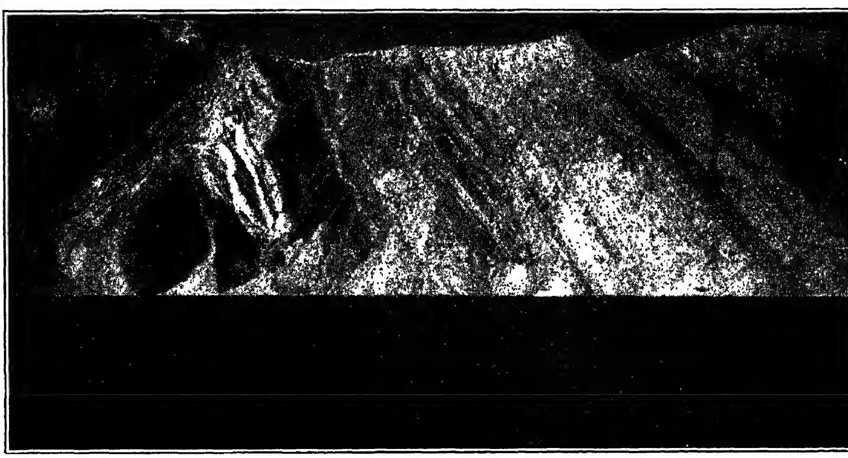


FIG. 111. Folded Strata, Ella Island, East Greenland.

The cliff is half a mile high. (Louise A. Boyd, Photograph.)

had been pushed in from one side. Wrinkles would rise, of course, but the actuating force is horizontally directed.

Furthermore, mountain ranges are not scattered and fortuitously oriented like so many crawling caterpillars on a map. There is system in their distribution. Most of them are near and parallel to continental margins. Some of them are rows of oceanic islands, yet they also are near and parallel to continental margins. And in the faulting and folding which have elevated them, the thrusts commonly have come from the ocean basins. Asymmetrical shapes of the folds may record the direction of thrust; low-angle faults may do the

same. Figure 113 shows the character of this evidence at a glance.

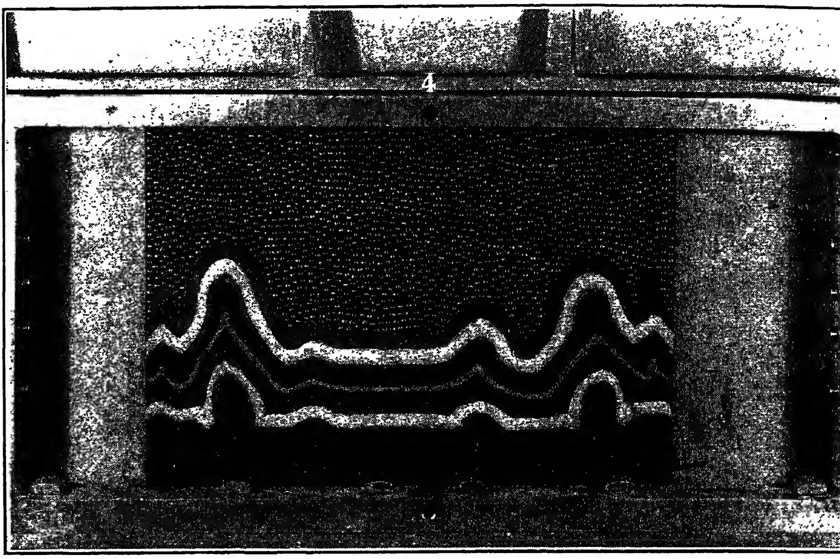


FIG. 112. Horizontal Layers of Sponge Rubber Folded by Lateral Compression under a Load of Steel Ball Bearings. (Museum of Science and Industry, Chicago.)

Differences in density of continental platforms and ocean basins. Don't conclude too hastily that mountain ranges owe

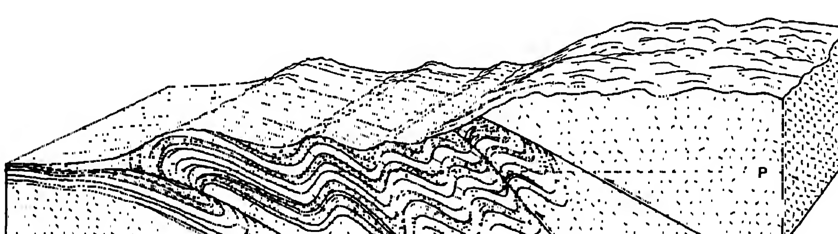


FIG. 113. Diagram of Asymmetrical Folds and Thrust Faults.

In which direction is the ocean? Compare these faults with the one shown in Fig. 107. The horizontal dashed line across the front of the block is a long look into the future. A forecast of what? (Longwell, Knopf and Flint, *Outlines of Physical Geology,* John Wiley and Sons, 1934.)

their linearity, their orientations, and their locations to some relationship between land and water. The problem goes deeper

than the bottom of the ocean, and the data are not yet all before you. Consider these two additional facts: (1) Lavas from oceanic volcanoes (the Hawaiian Islands, for example) have a higher specific gravity as a rule than lavas from continental volcanoes. (2) The attraction of gravity averages slightly greater over the oceans than over the lands. Both facts indicate that for some distance down in the outer shell or lithosphere, earth stuff is denser *beneath* the oceans than *beneath* the lands. Denser means heavier per cubic foot. And the surface of the *heavier* portions of the rock shell averages three miles *lower* than the surface of the lighter portions. If it were the other way, we should be nonplused, shouldn't we? Should you agree, you have grasped the fundamental idea. If you don't yet see the cause and effect—and mechanics—go back and re-read.

Wedge nature of platforms and basins. The prevailing theory among geologists today is expressed in the titles two of them have used for papers on the subject of diastrophism: "The Structural Failure of the Lithosphere," and "The Wedge Theory of Diastrophism." The inner earth is foundation for the outer. No large structure is stronger than its foundation. Gravity grips the entire earth, is constantly pulling everything centerward. If structurally the lithosphere consists of lighter continental and heavier suboceanic portions, and if their foundation should weaken, wouldn't the surface consequences be just what does exist—lighter parts higher, heavier parts lower?

Adjustments between platforms and basins. Increasing density and settling together of interior earth stuff will require radially directed downward movements. The continental platforms and ocean basins in this sense are great wedges (Fig. 114) of the lithosphere which must become jammed more tightly together by such settling. Since rock in large masses and under long-continued stresses is not perfectly rigid, deformation or failure is likely along the *contacts of the wedges.* This deformation will consist largely of *horizontal thrusting.* And mountain ranges near and parallel to continental margins are born!

When the Appalachian mountain belt was made and, in its

making, about fifty miles of the earth's circumference disappeared, there were comparable foldings in western Europe. The Atlantic Ocean heavy segment seems to have settled at this time, crowding against the margining continents, deforming the limestone, sandstone, and shale deposits that for millions of years had been accumulating in shallow marine waters near the continental margins. The settling was due to some kind of compaction or densification occurring in the earth's interior. The earth actually became smaller during the great diastrophism, its diameter less, its circumference less.

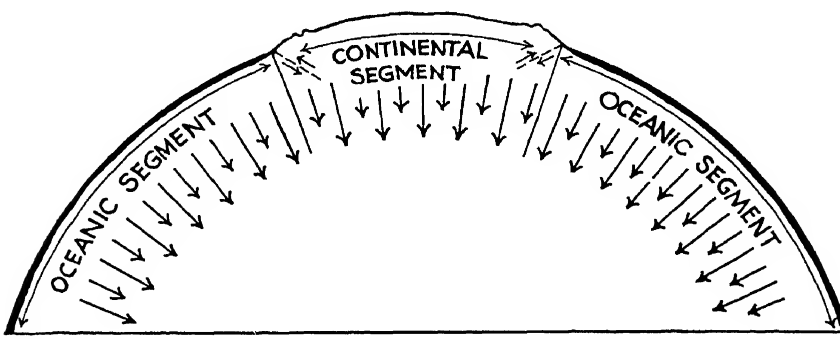


FIG. 114. The Wedges or Segments of the Lithosphere.

Arrows pointing toward the earth's center indicate the primary movements due to compaction or compression of the interior. Greater settling of ocean basins is shown by longer arrows. Long arrows parallel with the surface indicate the horizontal compression, as do also the wrinkles (mountain ranges) along the continental margins. (Chamberlin and Salisbury, *College Geology*, Revised by R. T. Chamberlin and Paul MacClintock, Second edition, Henry Holt and Co., 1933.)

Recurrent diastrophism. Mountain ranges of the earth are not all of the same age. Mountains along the Pacific coast of both North and South America are growing today, hence the repeated earthquakes. The Appalachians are so old that they have been peneplained once in their history and partially so in the interval following each of two subsequent non-folding uplifts of their stumps.* Over the geologically known earth, there are records in the rocks of something like a dozen different

* Restoration of eroded strata which these stumps represent indicates that if there had been no erosion during the Appalachian uplift, or since, the range would stand five miles high.

times of mountain-making, in one place or another. From this fact, which we can't take the space to prove, and the related fact that mountains are not enduring structures * we reach another fundamental conclusion regarding diastrophism. The premises are (1) that mountains rise faster than erosion can lower them, and (2) that after completion of growth, mountains are destroyed by erosion. The conclusion is that diastrophism (i.e., settling of heavy ocean basin segments, squeezing of lighter continental segments, folding of mountains) therefore occurs recurrently and does not occur continuously.

We know that movement along live faults is recurrent, with years of quiet between quakes, and with only a few inches or feet of movement each time activity occurs. Some such faults record a total displacement of many thousands of feet, which we believe to be the cumulative result of thousands of small movements during tens or hundreds of thousands of years. The idea fits the facts so well (the only alternative seems utterly fantastic) that we extend it to cover movements of the great earth wedges. The active times are mountain-making periods and the intervals of quiet we ask for are long enough for a cycle of erosion to be run.

Stresses in the outer lithosphere are caused by shrinkage of the interior. Sufficient rigidity exists to resist these stresses and they therefore accumulate. Something like knocking one brick out of a wall; the wall remains apparently as strong as ever. A dozen bricks may be knocked out and the wall remains though we think of it as weakened. The bricks above the hole look exactly as they did before, but that's because you can't see stresses. Another brick goes, and another, until accumulating stresses exceed the strength of brick and mortar and the wall abruptly fails. So in a way it is with the lithosphere and its recurrent great periods of diastrophism. Whatever takes place in the earth's interior to weaken the support of the continents and ocean basins occurs gradually. Failure is delayed, but it is inevitable. When it occurs, the ocean basins go down more than the continental platforms, the ocean water is drawn off

* On the airless and waterless moon, mountains should last forever.

the continental shelves. The continents, though not necessarily wedged up, become higher relative to sea level, mountains and plateaus locally are made, the lands are rejuvenated—and all the work of wind and water and ice for preceding millenniums is undone, must be begun again. One of those query marks can now come down!

There are many details in the picture which we cannot here consider. You must not be dissatisfied with it because of some item not explained. If the theory were inadequate, it would not be accepted, as it is, by most geologists today.

One detail may need attention, however, before we go further. In considering shore lines we found evidence that some coasts of North America had been recently emerged, some recently submerged. If that fact stands in your way, remember that the continent of North America, though three thousand miles across, is probably not more than a hundred miles *thick*. At something like that depth, or even less, earth stuff is probably uniform beneath continental platforms and ocean basins alike. Now, how rigid is a pancake of rock three thousand miles across? Isn't it perfectly satisfactory to think of the continent as being deformed differently in different places, especially if the ocean basin segments themselves settle unevenly or crowd unevenly on continental margins?

Mountains by plateau dissection. Not all mountains are the result of folding and faulting, not all are linear groups or ranges. The mountains of Rip Van Winkle's hideaway, the Catskills, constitute a group or cluster of big hills in whose bedrock there is essentially no folding or faulting. The Catskills have no trellis drainage pattern like that in the Appalachians. Ridges here are simply stream divides, peaks are higher places on these divides. Stream erosion has made the valleys, left the interfluves, in the dissection of a formerly nearly flat-topped plateau.

Such a mountain group of the future is already foreshadowed in the Grand Canyon of the Colorado (Fig. 115). Let existing tributary canyons continue to deepen and lengthen, let new ones develop, and the Colorado Plateau will, in its maturity, be

a maze of mountains of the Catskill type. Yet uplift was necessary before they could be made, uplift of the plateau type, elevation of great blocks of the lithosphere above their immediate surroundings to give the necessary steep stream gradients.

Volcanic mountains. Lone mountains, conical rather than ridged, composed invariably of lava materials; these mountains cannot be confused with any others. They are constructional forms, great dump heaps of volcanic materials which rose from far beneath the earth's surface through a conduit to the summit.

FIG. 115. "Mountains" in the Grand Canyon, Still Retaining Remnants of the Plateau Flat on Their Summits.

Air-plane view. Identical in origin with the star-shaped flat-topped butte in Fig. 45. (Fairchild Aerial Surveys, Inc., L. A.)

They may occur singly or in groups. Groups may be linear or irregular. Growth of volcanic mountains may still be going on or they may have had no additions for so long that erosion has destroyed their craters, gashed and furrowed their slopes. Indeed, only stumps or roots may remain to tell of their former existence.

Batholithic mountains. Akin to both volcanic mountains and mountains made by folding or faulting are those of another group, the batholithic mountains. It appears that when broad folding occurs, liquid magma may be squeezed up from con-

siderable depths. Some may escape, making volcanoes on top of the folded range. Much may remain beneath the upfold, cool and crystallize into granite or other related igneous rock, and come to constitute the core beneath the deformed sedimentaries, on which in turn the volcanic peaks are perched.

Or it may be that magma, rising for reasons other than folding, may fail to penetrate to the surface, may accumulate as great "blisters" beneath sedimentary rocks, making domes of mountainous proportions. Erosion, trenching subsequently into mountains with igneous cores, will reveal the part played by volcanism in their making.

BIBLIOGRAPHY

Agar, W. M., Flint, R. F., and Longwell, C. R., *Geology from Original Sources,* Chapter X, Henry Holt and Company, New York, 1929.

Allen, V. T., *This Earth of Ours,* Chapter VII, Bruce Publishing Company, Milwaukee, 1939.

Croneis, C., and Krumbein, W. C., *Down to Earth*, Chapters 16 to 19, incl., University of Chicago Press, 1936.

Heck, N. H., *Earthquakes,* Princeton University Press, 1936.

Probably no one knows more about earthquakes that have occurred in the United States. Dr. Heck's little book will tell you much that you may wish to know, after reading our brief half chapter on the subject of earthquakes.

Hobbs, W. H., *Earth Features and Their Meaning,* Chapters V, VII, and VIII, The Macmillan Company, New York, 1931.

Longwell, C. R., Knopf, A., and Flint, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939. Part 1, *Physical Geology,* Chapters 14, 15, 17.

CHAPTER XIII

VOLCANOES AND VOLCANISM

Though probably not one person in ten thousand has ever seen a volcano in action, everybody within reach of the Sunday supplement has seen pictures of the magnificent displays volcanic energy may cause. Many of us a few years ago heard a radio broadcast from the very edge of a lava flow descending the slopes of Mauna Loa, in Hawaii. Army aviators bombed this flow, hoping to divert or stop it! Many of us saw the film of Krakatoa's recent eruption in the East Indies. Some of us have glimpsed the great glacier-clad volcanic cones of Rainier, Baker, St. Helens, Adams, Hood, Jefferson, Shasta, and others, sitting astride the Cascade Range in Washington, Oregon, and California. Many have visited that unparalleled example, in Crater Lake National Park, of a volcano which destroyed its own cone. And who hasn't stroked a piece of polished granite or used kitchen scouring powder?

VOLCANIC ERUPTIONS. For spectacularity, nature has nothing to outclass explosive volcanism, nor has man, even if all his explosives were let off in one place. Are volcanoes safety valves? Are people in volcanic regions living over a munitions dump? What causes repeated explosions in the earth in certain places; why is hot and often liquid rock associated? Which is cause; which is effect?

Volcanic explosions discharge great clouds of dust-charged steam. The eruptions are due to steam and associated gases, not to dynamite nor TNT. Torrential rains often fall from the mushroom- or cauliflower-shaped cloud (Fig. 116), some of whose water comes from cooling of this steam. Water is certainly a constituent of the rising magma before the eruption, though some steam is created when the magma, on its way up, encounters ground water.

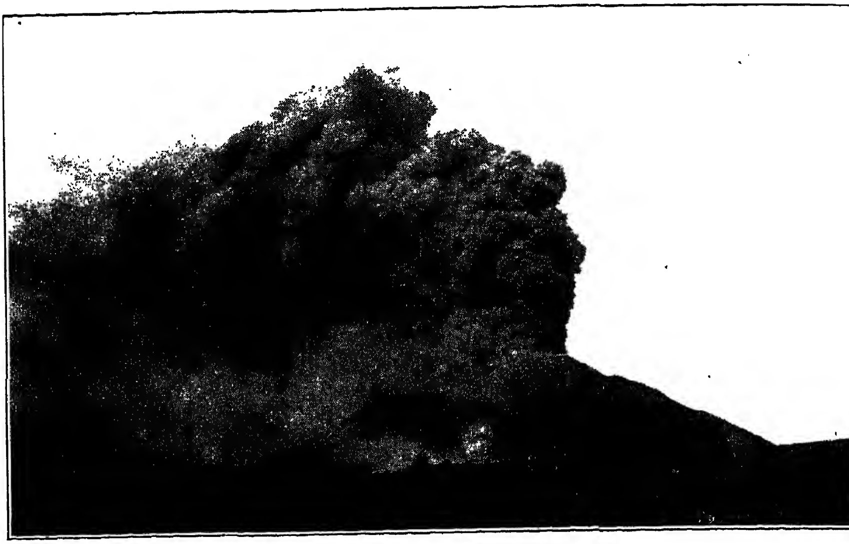


FIG. 116. Vesuvius on April 5, 1906.

The dust cloud is nearly a mile high. Mud rains are likely in the lee, under the cloud. (Frank Perret, "The Vesuvius Eruption of 1906," Carnegie Institution of Washington, Pub. 339, 1924.)

FIG. 117. Volcanic "Ash" Magnified Twenty-Seven Times.

Much of this looks like broken fibers of spun glass. (After A. Johannsen, *Descriptive Petrography of the Igneous Rocks,* University of Chicago Press, 1931.)

EJECTED PRODUCTS. Many features of the ejected products of volcanic eruptions testify that this gas is *dissolved* in the magma. Eruptions don't simply hurl out great chunks of solid rock. They most commonly discharge a vast cloud of "ash," which is chiefly the result of instantaneous freezing of the fine liquid lava spray the explosion produced. Some-

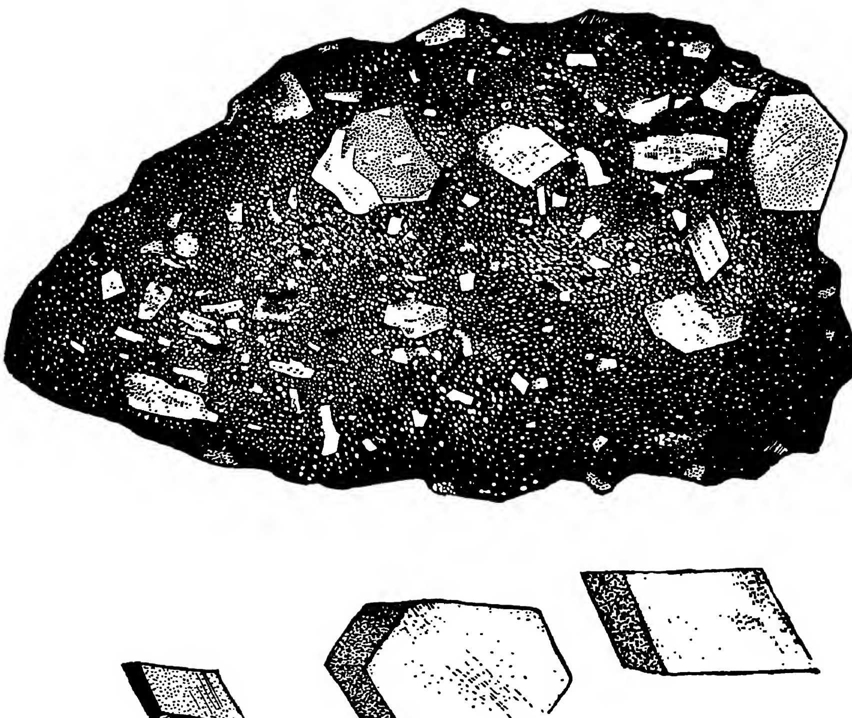


FIG. 118. Crystals in a Ground Mass of Uncrystallized or Minutely Crystallized Material. (After Grout, *Petrology and Petrography*, McGraw-Hill Book Co.)

thing like the explosive foaming of an overcharged carbonated beverage. Indeed, there is such a thing as frozen lava foam, though we call it pumice. The minutely porous structure of pumice, with all pores sealed so that it floats for months, is similar to the porous character of leavened bread—non-explosive gas expansion in a viscous liquid, followed by a solidification of the liquid. Volcanic dust, or "ash," under the microscope, is

simply an aggregate of sharp-edged fragments of glass. Its differentiation from dust made in all other ways is very easy. Its value in kitchen scouring powders is obvious.

Where there is insufficient gas originally, or gradual release of it is possible, lava is not explosive. It may escape from the vent fairly quietly and flow down the slope of the volcanic cone, chilling, thickening, freezing solid before reaching the bottom, adding to the bulk of the cone. This lava may be sparingly porous, is likely to be partially crystalline, partially glassy, when cold. The glass represents the lava minerals that did not have

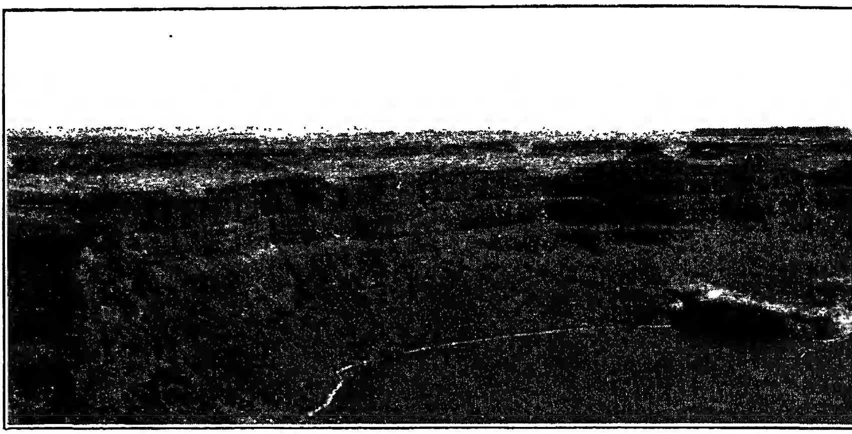


Fig. 119. Part of the Succession of Lava Flows That Made the Columbia Plateau.

The cliff is 400 feet high and each of the three flows showing is about 75 feet thick. Stratified rock, yet not sedimentary! There was time enough between successive outflows for each flood to freeze to the bottom, even for trees to grow on the surface. Moulds of the charred trunks are found between flows. Charred? (Frank Guilbert, Photograph.)

time to crystallize out; the crystals can be identified under the microscope as definite minerals (Fig. 118). Even these glassy lavas, when re-heated in the laboratory to the fusion point, may suddenly froth up into a pumice, for some gas is still dissolved in them.

Fissure flows. Beside the variability of gas content in lavas, there is another variable to consider. It is the excess heat, the temperature (the figure doesn't matter) *above* the lava's freezing point (whatever that may be). Gas-free lavas

with, say, 200 degrees of excess heat will flow almost as freely as water, will get far from their discharging vent, may on favorable topography spread widely before the temperature drops enough to stiffen and thicken them. Lavas with low freezing points *and* high excess heat don't even build cones; they spread as nearly level sheets over many square miles of country. Iceland has had such flows in historic times, inundating and burying farm land in a fertile valley. Yellowstone's geysers are the last cooling stages of geologically rather recent fissure flows. The black volcanic glass of Obsidian Cliff is a part of one of the flows. The Columbia Plateau of Washington, Oregon, and Idaho is largely determined by a great series of these flows, more than half a mile thick in places, which buried a rugged land of maturity and started the cycle all over again on the new surface (Fig. 119). Because the fissures conducting up from below don't clog with quickly frozen lava, no series of separate vents is formed along them, no line of cones record the lava leakage. Hence the name, *fissure flows.*

INTRUSIONS. Streams trenching into the Columbia Plateau have in some places cut down to the older rock beneath and exposed the nearly vertical fissures through which the lava rose. They are essentially joints, their walls spread apart and the space filled with lava that never succeeded in reaching the surface (Fig. 120). Such igneous rock is *intrusive,* and the structures are *dikes.* Elsewhere the rising magma has lifted the overlying rock without breaking through, has spread laterally along bedding planes, literally splitting the strata apart, then cooled in place. *Sills,* thus formed, are geometrically similar to dikes, but they take nearly horizontal positions. The great "blisters" of intrusive rock referred to earlier as *batholiths,* may be fifty miles across and are of unknown depths. At the time of intrusion they raised, or were forced in beneath, large areas of older rock, making mountainous uplifts. Swarms of marginal dikes and sills branched out from them into the overlying rock, now clearly revealed where streams and glaciers have eroded trenches through to the batholith. Batholith rock is

dense and completely crystallized; without pores or glass, unlike quickly cooled surface lava. Granite is a product of the slow cooling of batholithic intrusions. Smaller blisters, a few

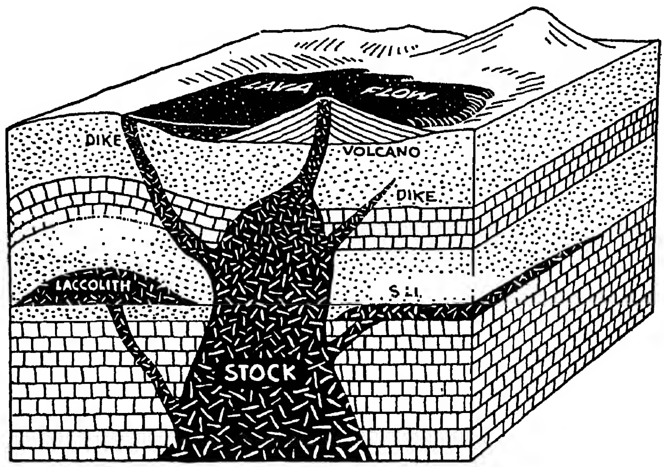


FIG. 120. Intrusions, Extrusions, and Their Relations. (After Emmons, Thiel, Stauffer and Allison, Geology, Second edition, McGraw-Hill Book Co., 1939.)

miles across, a few hundred feet thick, whose bottoms are known from subsequent erosion, are *laccoliths*. Even the feeding dikes have come to light beneath some much eroded laccoliths.

VOLCANIC REGIONS. Volcanoes are gregarious. They like to cluster along continental (or oceanic) margins and growing mountains. There are striking similarities between maps of seismic and volcanic areas (Fig. 121). The "ring of fire" around the Pacific is also a ring of quake-shaken tracts. The East Indies have too many of both, so does the northern side of the Mediterranean. Undoubtedly the earth's internal energies, more freely released along the contacts of the great wedges than elsewhere, produce both expressions of activity in such places. Live batholiths of the present we are not certain about, but it's a fair guess that regions of numerous active volcanic vents, and accessory steam and gas vents, are underlain by batholithic intrusions still liquid.

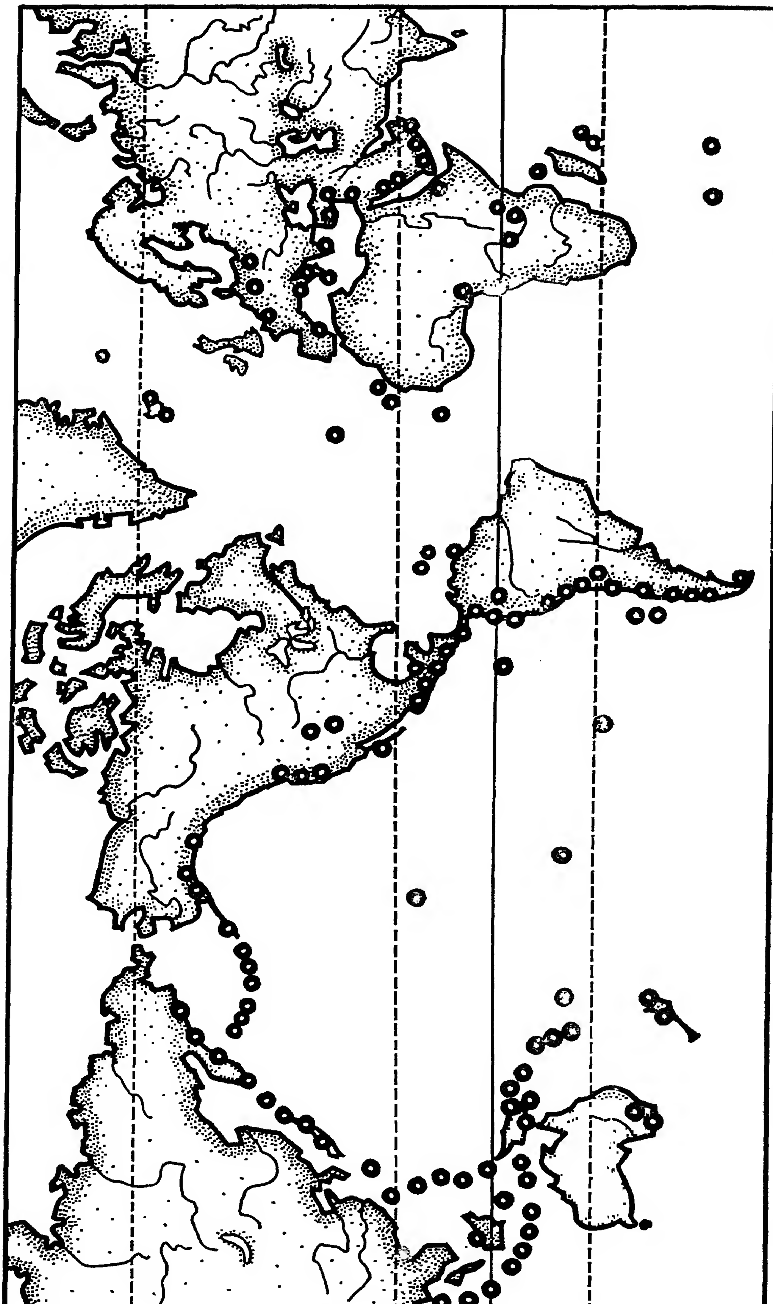


FIG. 121. Volcanic Activity, Recent and Present. (After Allen, *This Earth Is Ours*, Bruce Publishing Co., Milwaukee, 1939.)

Contact metamorphism. Rock intruded by magma must necessarily become heated. It may simply be "baked," it may become chemically altered, it may even become partially dissolved in the intrusive liquid rock. Magma is not simply melted mineral matter. It contains dissolved gases of which water is the chief one. They tend to escape into cracks and pores of intruded rocks and, because of the very high temperatures, they cause chemical changes which may greatly alter the rock they penetrate. This is *contact metamorphism* (Greek for changed in form, structure, character).

Ore veins. The gases and liquids emanating from an intrusive mass produce results we can't duplicate in our laboratories. Some of these results are of great economic importance. Veins of gold-bearing quartz penetrating the roof rock of batholiths are one example. Precipitation of compounds of silver, nickel, copper, lead, and other metals may come from magmatic water released as a batholith slowly crystallizes, water which cools or encounters other depositing conditions in the surrounding rock.

Causes of volcanism. There are numerous unsolved problems for the geologist in the subject of volcanism. We encountered one of them in the first page or so of our discussion of the solid earth. If the earth is as rigid as tool steel, where does the high-temperature liquid rock come from? Suppose we suggest an adequate explanation, one that calls for *local liquefaction* where temperatures may be abnormally high, or where rock of unusually low melting point may exist, or where diastrophic relief of pressure may lower the melting point of any material at that place. We immediately encounter another question, even more fundamental, even more difficult to answer.

For many years we had a satisfactory answer to that more fundamental question.* It was satisfactory until the seismograph was invented, radium was discovered, and a former glaciation of northern North America was established. Then

* Namely, the origin of the earth's internal heat.

we learned from the seismograph that our earth was not a molten globe, frozen over with a crust a few miles thick. From records of former glaciation we learned that the earth's surface has not been undergoing a progressive refrigeration, but had several times staged comebacks to milder climates—a procedure out of harmony with the cooling earth theory. From discovery of radioactivity * we began to suspect that the earth, though losing heat along the geothermal gradient, might actually be getting hotter inside. So the beautiful theory of a generation ago was murdered, as Huxley says, by a gang of brutal facts.

But it is because science is never sure of anything that it is always advancing. Somebody once said that science never solves problems; it simply advances them. What we need in order to establish any satisfactory theory for the source of the earth's internal heat is better and more complete information. Facts may be stupid things in themselves, but theory without adequate factual background is mere mental gymnastics.

We are very close, right now, to one of the largest questions man has ever asked of his planet. Whence came the earth originally? This little book modestly declines to discuss the question.

* Radium comes from minerals, constituents of rock. In the constant atomic disintegration of radioactive minerals, heat is generated and discharged.

BIBLIOGRAPHY

Agar, W. M., Flint, R. F., and Longwell, C. R., *Geology from Original Sources,* Chapter IX, Henry Holt and Company, New York, 1929.

Allen, V. T., *This Earth of Ours,* Chapter I, Bruce Publishing Company, Milwaukee, 1939.

Croneis, C., and Krumbein, W. C., *Down to Earth,* Chapters 20 and 21, University of Chicago Press, 1936.

Hobbs, W. H., *Earth Features and Their Meaning,* Chapters IX and X, The Macmillan Company, New York, 1931.

Longwell, C. R., Knopf, A., and Flint, R. F., *Textbook of Geology,* John Wiley and Sons, Second Edition, 1939. Part 1, *Physical Geology,* Chapter 13.

Loomis, F. B., *Physiography of the United States,* Chapter VIII, Doubleday, Doran and Company, Garden City, 1937.

CHAPTER XIV

THE EARTH'S HISTORY

General nature of the record. Very briefly we have sketched through the subjects presented in this book. Not only are there entire books on each of the main topics discussed, but many of the subordinate topics here dismissed after a paragraph or so have whole books devoted to them. Furthermore, we have considered only one aspect of geology, the changes now occurring in the earth. The rocks of the lithosphere constitute a great archive, once we know how to decipher the record. Like the story of the Pharaohs, events long past are written in stone. Geology's chief theme is the history of the earth. In this book we learn only the alphabet. All we can hope to do in the last chapter is to see how the deciphering is done and what the large features of the record are like.

History is more than a record, it is an explanation of cause and effect. What the world of men is like today depends enormously on what it was like ten or twenty years ago; what it will be twenty years hence is foreshadowed today. Similarly, cause and effect ruled rigorously in the world before man, have equal sway over his present physical environment. The larger present-day relationships outlined in this book have existed throughout the recorded past. Said one of the great men of the early days of geology, "The Present is the key to the Past." A hundred and fifty years of increasing understanding has established his theory as a fundamental principle of earth history.

There was an earth long before the earliest rock records were made. It may well be that much more time elapsed in these unrecorded stages than since the record began. Perhaps the young earth was entirely molten, perhaps it grew slowly

for eons by the infall of meteoritic bodies more abundantly distributed in the solar system than now. Perhaps you prefer some other idea. All we can do with these concepts of prerecord conditions is to insist that they harmonize with the principles of chemistry, physics, and astronomy and with the record when it begins.

The earliest records tell of a hydrosphere and an atmosphere acting on a lithosphere; tell of climates which, though differently distributed on the earth, did not range outside the extremes of hot and cold, wet and dry, we have today; and tell of volcanism and diastrophism whose activities did not greatly exceed those of later times. But the earliest records do not tell specifically of life on the earth.

How do we know there was a hydrosphere and an atmosphere so many millions of years ago? Answer the query from this clue—the oldest rocks are stratified sediments! Wasn't weathering necessary if there was to be land waste for making sediments? Were not streams required for transportation to the place of deposit? Does not the stratification record sorting during the transportation? Are not water bodies a requirement for the deposition, as well as a source for the rain that aided the weathering and supplied the streams? Remember, I am not saying that this early earth was identical with ours today. It was similar. It was not a molten globe then, if it ever had been. It was not so hot that all water was kept in the form of an atmosphere of steam. Nor was it so cold that all water was solid ice.

Detailed corroborative evidence is ours, should some one want to argue that this early stratified rock was made in "some other way." There are ripple marks on the rock slabs, made by waves when the material was loose sand. Drying cracks, also, like those you see where a mud puddle dried up a few days ago. Cross-bedding, made by stream currents and air currents today, is duplicated in some of these ancient sediments. There were early deserts where winds sorted the sand, deposited dunes, etched pebbles; where evaporation left layers of rock salt and gypsum. There was glaciation so remote that the theory of a

thin crust over a molten globe in these early times must be rejected. Striated "pavements," striated pebbles and boulders embedded in an unsorted matrix; all the kinds of evidence—except one *—which we accept for that rather recent glaciation of the northern half of North America.

Life of the past is recorded largely by fossils. Petrified wood or shell or bone is familiar to everyone. The organic material was buried in sediment, then circulating ground water later deposited mineral in place of the slowly decomposing organic matter. Perhaps only imprints are left, like those of leaves, or the tracks of animals. They are just as convincing as petrifactions.

Life may also be recorded by organically derived substances, like oil, gas, coal, even though no fossil forms are contained. Most limestone is a solidified lime mud derived from calcareous hard parts of various organisms. But calcium carbonate may be precipitated chemically, as well as biochemically, so its testimony in the absence of fossils is not convincing. Coal or scattered carbonaceous matter in sediment may become altered to the pure carbon form of graphite. Since we are not sure that all carbon in rocks is organic in origin, we play safe in saying that the earliest indubitable record of life on the earth is that of the oldest actual fossils, about halfway back in the total rock record.

Fossils certainly testify to a hydrosphere and an atmosphere much like the present ones. Venus with an atmosphere almost all carbon dioxide and so dense that astronomers never have seen to the bottom of it can't be a parallel, nor can Mars with almost no water vapor in its atmosphere and no oceans on its surface.

Our fossil record also tells of the climates of the past. What but a former mild climate can explain petrified tree trunks ten inches across in east Greenland where trees today do not exceed eighteen inches in height and one inch in trunk diam-

* The missing one is topography. After reading the story of gradational activity, we could hardly expect survival of moraine forms for hundreds of millions of years.

eter? What else can explain fossil coral reefs in limestone about the shores of Hudson Bay?

Fossils are even more important to the geologist in another way. They are the dates on the tables of stone, on the pages of the book of earth history. One of the foundation blocks of Darwin's theory of organic evolution was the known progressive change in fossil plant and animal forms from the time the record of life began until the present. Earlier thinking had asked for a series of wholesale extinctions and special new creations. This was an impossible theory when it became obvious that thousands of species had appeared, flourished, declined, and become extinct at hundreds of different times, and that there never had been any really wholesale extinctions.

ORDER OF SUPERPOSITION. A simple idea, conveyed by the phrase *order of superposition*, is an essential part of the principle of dating by fossils. It is that in any series of sedimentary rocks, the lowest formation is the oldest, the uppermost the youngest, the succession from bottom to top is one of age as well as of position.* Consider the great section in the walls of the outer gorge of the Grand Canyon of the Colorado (Fig. 122). In the lowest strata containing a record of life there are species of fossils not found in any younger layers. In every formation of that series are fossil species which are limited to it. The time of deposition was the life span of the contained index species. We don't need them here to tell the relative ages of the formations; the order of superposition does that. But in New York, or in Tennessee, or dozens of other places in the country, are strata containing fossils peculiar to that lowest formation in the Grand Canyon. They are therefore of the same age! The principle applies to the entire world. We correlate stratified rocks of Australia, or Asia, with those of North America on the basis of the contained date-marking fossils. Even under the discarded special creations theory, the principle holds good.

* Even though deformation has occurred, this order of superposition can generally be determined.

FIG. 122. Sedimentary Record in the Grand Canyon's Walls. (U. S. Geological Survey.)

UNCONFORMITIES. One more principle necessary in reading the geological record, and we are done. The Grand Canyon will again serve as an example. Downstream from the inner or granite gorge, sedimentary rocks constitute the entire section. But only in the upper half of the wall are the strata horizontal. A definite dividing line can be drawn on Figure 122 between horizontal beds above and tilted (and faulted) beds below. Draw it. The tilted beds were horizontal when deposited and their present attitude can only be the result of later diastrophism. The deformation did not affect the beds above, and only because those beds did not exist when the movement occurred. The diastrophism therefore was an interruption in the sedimentation recorded in the canyon wall. It occurred after the youngest of these deformed beds were made and before the oldest beds of the upper undeformed series were deposited.

Compare this with the record of past diastrophism in the Appalachian Mountains. One difference is that the Appalachian deformational structures are not buried beneath later sediments. Instead, they underwent profound erosion and then uplift again. Did these buried inclined beds of the Grand Canyon suffer erosion after their tilting and before deposition of the horizontal series above them? *

The contact we are considering is an *unconformity*. It is a record of diastrophism that can be dated as after the time of the so-and-so fauna (the assemblage of fossils in the uppermost tilted formation) and before the time of the such-and-such fauna (in the lowest horizontal formation). How long after? How long before? Isn't it like dating the Revolutionary War as after the discovery of America and before the Spanish-American War? In what is now the Colorado Plateau, something else happened in that interval. When you removed the overlying horizontal strata you uncovered a buried land surface, an erosional surface with truncated tilted strata like the Ap-

* If you hesitate in answering, suppose you remove the overlying horizontal series, leaving exposed the surface of the tilted beds as they were when sedimentation was renewed, after the diastrophism.

palachians today, with hills that suggest hogbacks and lowland flats across softer strata. The unconformity is a record also of erosion after the diastrophism but before the deposition of the overlying strata.

How much erosion? You would hardly care to assert that the beds in the summit of the buried hill are the youngest ever deposited in the region before the diastrophism. Plenty of rock became altered to soil on that hilltop and was carried off as slope wash * during the shaping of the buried landscape. Nothing in this Grand Canyon section can tell us how much erosion occurred. Nothing tells how long, geologically, was the interval represented by the unconformity, how much geological time was taken by the diastrophism and the erosion. Nothing but the fossils!

The waste of that old land surface was taken somewhere and was there deposited as sedimentary rock! Probably we never shall identify any sediments as derived from this region at this time. But we do know of places where, without unconformity, a sedimentary series grades all the way up from strata containing the so-and-so fauna to strata containing the such-and-such fauna, a complete sedimentary record of the lost interval in the Grand Canyon section. The fossils, as date markers, are simply invaluable. Nothing else we have yet found in the rocks makes such long-range correlation possible or enables us to date (geologically) intervening times of diastrophism, volcanism, or erosion.

FUNDAMENTAL FEATURES OF THE HISTORY. The insistence in preceding pages on similarity of past and present may lead one to think that the earth has had a simple and monotonous history, the same thing or the same balancing of things, over and over, throughout its life thus far. About as monotonous as human history, I would say. The same patterns reappear, just as they do in fiction, the drama, politics, industry, international relations, almost every human activity. There are

* Certainly I do *not* mean the canyon slopes. In terms of the stratified rock record, when was the canyon begun?

only two features of the earth cinema that are not repeating patterns, radioactive disintegration and organic evolution.

Had earth history, staged with "platforms" and "basins" as backdrops, consisted of gradational changes alone, a universal ocean would long ago have spread across the continental stumps. The platforms would still have existed, so would the great basins, but only atmospheric and oceanic changes would have continued. Without land, they leave no record. Land would all have disappeared, life would all have been marine. This picture isn't at all fanciful; it has been well along toward realization several times in earth history.

In the Grand Canyon section, most of the sedimentary rocks are marine deposits. In the Appalachians, the folded sedimentary rocks are largely marine. The Great Lakes states are underlain by marine sedimentary rock. More than nine-tenths of the Mississippi drainage area has stratified marine deposits for its bedrock. The Atlantic coastal plain spreads out over old sea floor, so does the Gulf coastal plain. The catalog doesn't end with this list, for two-thirds of the surface rock of the continent, of all continents, is of marine origin.

The inescapable conclusion is that sea water has stood over such areas for long periods. But not a universal ocean. There must have been land areas during such times, sources of the waste that made the sediments, but it is less easy to decide just where and how extensive the lands were. We are fairly confident of two things, however. The present ocean basins were not land and the present lands were not part of ocean basins. All that these extensive marine deposits record is a series of *relatively shallow* overlaps of ocean water on the continents, like the shallow water on the continental shelves today, like the shallow North Sea and Baltic Sea of Europe and the shallow Hudson Bay of North America.

The evidence for these conclusions is convincing. None of the marine limestone or shale or sandstone is like deep-sea ooze or red clay. All have ripple marks, fossils of shallow-water animals, coarser phases deposited near shore, even old beach gravel and river delta material incorporated in them.

These widespread marine deposits commonly rest on buried landscapes of low relief. Rarely are buried hills found, like that in Fig. 122. The sea appears to have flooded over low, peneplained, or almost peneplained, land surfaces nearly every time it spread back into continental interiors.

What caused the continental floodings? Figure it out this way for one plausible explanation. The present average altitude of the lands of the earth is half a mile. The land area is about 54,000,000 square miles. If 54,000,000 square miles $\times$ ½ mile were dumped into the ocean, 27,000,000 cubic miles of water would be displaced and *sea level would be raised some 600 feet.* A denudation of the continents considerably less than that, produced by the slow progress of baseleveling, would provide for any of the marine transgressions of the land the past has witnessed.

We think therefore that there were long periods when diastrophism was quiescent and gradational agents got far along in their work of destroying land. As the dust, mud, and sand were deposited in the ocean, the sea level slowly rose and salt water flooded back on the lower portions of the continents. The fine texture of the waste material indicates that the surviving lands were low, their streams inadequate to carry coarse detritus. Limestone is considered to be a record of clear water, almost no land waste coming in. Only very low land could be marginal to a lime-depositing sea.

We know from the extent of some of the ancient marine deposits that as much as 60 per cent of North America has been beneath shallow seas at one time (Fig. 123), that Arctic waters have actually mingled with those of the Gulf in mid-continent, that embayments of the Pacific and Atlantic have met in the interior.

Reconstructions of ancient geography are possible only with index fossils, species that lived in all the seven seas but lived only a short time geologically. The Trenton limestone (the record of the 60 per cent submergence) can be recognized in almost any outcrop by its particular assemblage of index fossils. Well records tell of its presence beneath later sediments. We

restore it on the tops of eroded upfolds. By such reconstruction, paleogeographic maps are made.

We must now look at another kind of record in the earth's history, the unconformities. They are records of erosion,

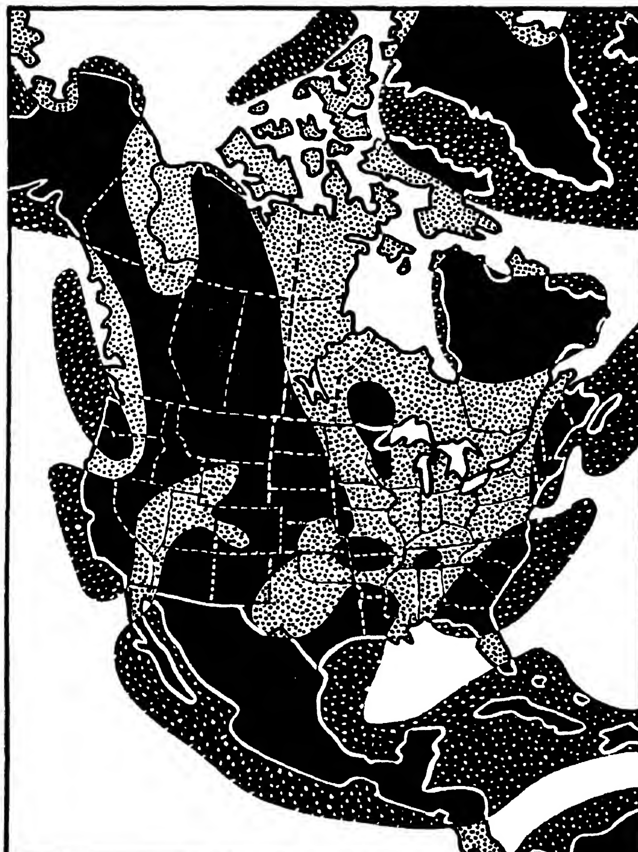


FIG. 123. The "Trenton" Submergence in North America.

Black areas, including those with white dots, presumably were land during Trenton time. (After Shuchert and Dunbar, *Textbook of Geology*, Pt. II, John Wiley and Sons, 1933.)

therefore of withdrawal of the sea, therefore of diastrophism which lifted the shallow continental sea floor above ocean level, and often warped or folded it in that movement. They represent missing pages of the stone tablets, some torn out by ero-

sion, some failing to be written while the area was land. Unconformities are not universal. Somewhere there must be a sedimentary record of the time an unconformity represents. It may be off the edge of the platform, in the deep sea and therefore inaccessible. Or it may be on some other part of the continent, some part remaining submerged while the erosion that made the unconformity was occurring.

A valid generalization is that any extensive unconformity in any one continent's record is duplicated by one of similar age in other continents. That is to say: when one continent comes up pretty much out of water, all do. Or, when oceanic segments settle, sea level must be lowered the world around. We are back again to the wedge theory of diastrophism. The idea of recurring diastrophic activity, born of the occurrence of successive generations of mountains and their subsequent demolition by erosion, is supported by another line of evidence, the contemporaneous unconformities in the sedimentary records of the different continents.

The rhythm of earth history, the great repeating pattern, is therefore determined by accumulating stresses in the lithosphere. Recurring times of adjustment between the lighter and heavier wedges, repeated emergence of the worn-down continents, rejuvenation of lands by mountain- and plateau-making constitute one end of the pendulum's swing. That attained, diastrophism rests and the swing turns back toward gradation. Destruction of land ensues, the highlands bow to the inevitable, worn-down lowlands increase, the sea level rises, shallow marine floodings invade the continents, deposition replaces erosion in the invaded areas, hundreds of feet of stratified sediments accumulate, organic remains in fashion at the time are entombed. The pendulum has swung to the other end. Since evolution has never reversed or repeated, the record thus becomes dated.

When the earth's interior settles down to equilibrium (stops shrinking), diastrophism will cease, the great recurring rejuvenations of the continents will come to an end, and solar energy's unwavering ambition will be realized. Millions of

years before that consummation, the human race will have vanished. We are very important, but only to ourselves. The earth got along satisfactorily for a cool two billion years before our species appeared; it will manage without us again. The earth needs us far, far less than we need it.

Sedimentary rocks contain evidences of glaciation where now moderate climates exist—and the reverse. Aridity has prevailed in now humid regions—and the reverse. Is there rhyme (rhythm) or reason in the earth's past climatic vicissitudes?

There are both. We can date the glaciations or the aridities just as we do the diastrophisms or volcanisms or erosions, by reference to fossil-bearing rocks older (below), and younger (above). From the dating, we learn that glaciations and aridities have both closely followed marked diastrophic activity. They have occurred when lands have been extensive and high, when continental climates have been favored. The mild climates of the past, with little differentiation in latitude, have prevailed when the spread of oceanic water was greatest, when oceanic climates were favored.

The argument is that changes in geological climates are the result of different redistribution of solar radiation after its reception by the earth, such as better functioning of ocean currents, less chilling of air in contact with high latitude land—or the reverse. That isn't the whole story. The sun is a variable star. It has had an observed 10 per cent variation in its energy output. Perhaps the past has witnessed larger variations. Certainly climates on the earth would respond to such changes. But how explain that rhythm in harmony with the diastrophic rhythm?

Any present-day climate has a multitude of causal factors. Climates of the past must have been similarly complex. Let's say that variability of the sun's energy discharge is but one factor, and not enough to make the great changes on record. Let's say that the climatic consequences of diastrophism are a little short of adequate. Though the two rhythms have no

causal connection and are not timed for the same intervals, now and then there will be coincidence and the combination of favoring solar and terrestrial factors will yield the recorded result. It will be timed for diastrophism.

For the sedimentary record of glaciation and aridity, we must depend on deposits made on the land. Moraines and dune sand so accumulate today. Rock salt beds will need interior closed basins, like Great Salt Lake of the present. For gypsum, lagoons and shallow bays along the coast, and replenishment with sea water as evaporation occurs, are required.

In the turmoil of all the multifarious changes where air and water and land make contact are the earth's living forms. They are biochemical and biophysical mechanisms; they couldn't exist without energy sources. It is solar energy, chiefly, which runs them. Life has existed probably more than a billion years; its record goes back eight hundred million. Always it has been in this zone of turmoil, of energy discharge, of infinitely varied and constantly changing habitats. And always the living forms that survived have done so by adapting to changed depth or circulation or turbidity or temperature or salinity or humidity, as well as to each other. You may well have raised the question before I could get to it; what paleontological record exists of the earth's great rhythm?

Since there are land-deposited sedimentary rocks, as well as marine, we have fossils of land animals and plants for amplification of the record. They are important as recorders of climate, though less important for correlation and dating than those of the marine animals. Marine organisms may spread around the world, land forms are likely to be isolated on individual continents. But all tell unequivocally of great changes in area and nature of land and sea.

Spreading shallow seas opened new worlds to the marine forms. In countless millions they invaded the continental interiors, in countless millions their shells and skeletons occur in the limestone bedrock of any one of the Great Lakes or upper Mississippi Valley states. Great proliferation of new

kinds (species) occurred at such times; evolution was rapid and expanding.* Abundant room and food and warm water, what more could be desired by clams or corals?

But when the seas drained off as the continents emerged at diastrophism's command, hard times beset the marine faunas. Only narrow marginal shelves of shallow water remained; the water was turbid (increased land areas); the warm currents were restricted. Great numbers of species became extinct; few new ones were evolved. Over and over, perhaps a dozen times in the stratified rock record, the marine faunas returning to continental interiors were greatly altered from those that retreated when the last diastrophism drove them out.

The record of land life tells of climatic changes more striking than the oceanic record can contain. Land plants are sensitive to cold and heat, to dry and humid conditions. Floras associated with glacial deposits confirm our interpretation of the striated bedrock. Forests once covered the treeless Great Plains and Great Basin of the West; increasing aridity has driven them out. The cold-blooded reptiles keep to warm climates, have migrated out of high-latitude regions when continental expansions occurred, into them as seas expanded and milder climates came. Nature's rather late invention of warm-blooded mammals and birds is all that gives the Arctic a land fauna today. Whole books are written on these themes, books not restricted as we are here.

Late in the evolutionary story comes man. Gifted with a certain amount of intelligence, he is able to command and control in many ways. But he is greedy and has little thought for the future of his kind. What will some "visitor from Mars" find when he examines the record man left? Removal of the great deposits of metallic ores, of coal, of oil and gas, surely. Widespread destruction of soil, probably. Interrupted regimen of rivers by dams, canalization, levees, irrigation ditches, also. Will he find evidence that man at last learned to use his earth

* I do wish it were possible to tell you more than that simple generalization.

wisely? That depends on the coming generations; it hasn't yet been learned by the majority of people at the time this book is written.

BIBLIOGRAPHY

AGAR, W. M., FLINT, R. F., and LONGWELL, C. R., *Geology from Original Sources,* Chapter XIV, Henry Holt and Company, New York, 1929.

ALLEN, V. T., *This Earth of Ours,* Chapters X to XIV, incl., Bruce Publishing Company, Milwaukee, 1939.

CRONEIS, C., and KRUMBEIN, W. C., *Down to Earth,* Chapters 25 to 28, University of Chicago Press, 1936.

BIBLIOGRAPHY

All books referred to at the ends of chapters are listed here. The "Preferred Books for Supplementary Reading" should be in every library in quantity sufficient for convenient use by students. Those under the heading "Additional Books for Supplementary Reading" are desirable as reference books, and at least one copy of each should be in the library if possible.

Preferred Books for Supplementary Reading

Brooks, C. F., *Why the Weather,* Harcourt, Brace and Company, New York, 1935.

Finch, V. C., and Trewartha, G. T., *Elements of Geography,* McGraw-Hill Book Company, New York, 1936.

Kirby, Lieut. Harold L., *An Analysis of Meteorology, as Related to the Operation of Aircraft,* The A. H. Clark Company, Glendale, 1939.

Longwell, C. R., Knopf, A., and Flint, R. F., *Textbook of Geology,* John Wiley and Sons, New York, Second Edition, 1939.

Marmer, H. A., *The Sea,* D. Appleton-Century Company, New York, 1930.

Trewartha, G. T., *An Introduction to Weather and Climate,* McGraw-Hill Book Company, New York, 1937.

Additional Books for Supplementary Reading

Agar, W. M., Flint, R. F., and Longwell, C. R., *Geology from Original Sources,* Henry Holt and Company, New York, 1929.

Allen, V. T., *This Earth of Ours,* Bruce Publishing Company, Milwaukee, 1939.

Bartky, Walter, *Highlights of Astronomy,* University of Chicago Press, Chicago, 1935.

Beebe, William, *Half Mile Down*, Harcourt, Brace and Company, New York, 1934.

Croneis, C., and Krumbein, W. C., *Down to Earth*, University of Chicago Press, Chicago, 1936.

Dake, C. L., and Brown, J. S., *Interpretation of Topographic and Geologic Maps,* McGraw-Hill Book Company, New York, 1925.

Heck, N. H., *Earthquakes*, Princeton University Press, Princeton, 1936.

Herdman, Sir William, *Founders of Oceanography,* Edward Arnold and Company, London, 1923.

Hobbs, W. H., *Characteristics of Existing Glaciers,* The Macmillan Company, New York, 1911.

Hobbs, W. H., *Earth Features and Their Meaning,* The Macmillan Company, New York, 1931.

Johnstone, James, *A Study of Oceans,* Edward Arnold and Company, London, 1926.

Koeppe, C. E., *Weather and Climate,* McKnight and McKnight, Bloomington, 1935.

Lobeck, A. K., *Geomorphology,* McGraw-Hill Book Co., Inc., New York, 1939.

Loomis, F. B., *Physiography of the United States,* Doubleday, Doran and Company, Garden City, 1937.

Lord, Russell, *To Hold This Soil,* U. S. Department of Agriculture, Miscellaneous Publications 321, Washington, 1938.

Marmer, H. A., *The Tide,* D. Appleton-Century Company, New York, 1926.

Murray, Sir John, *The Ocean,* Home University Library, Thornton Butterworth, Limited, London, 1931.

National Geographic Magazine, National Geographic Society, Washington, D. C., June, 1931; April, July, December, 1934; October, 1935; January, May, 1936.

National Geographic Society, Washington, D. C., *Stratosphere Series* No. 1, 1935; No. 2, 1936.

Oceanography, The National Research Council of the National Academy of Sciences, Washington, 1932.

Raisz, Erwin, *General Cartography,* McGraw-Hill Book Company, New York, 1938.

Sharpe, C. F. Stewart, *What Is Soil Erosion?* U. S. Department of Agriculture, Miscellaneous Publications 286, Washington, 1938.

Tannehill, I. R., *Hurricanes,* Princeton University Press, 1938.

GLOSSARY

AGGRADATION. The raising of the level of a land surface or sea bottom by deposition on it.

ALLUVIAL FAN. A fan-shaped deposit made along a stream course where gradient is notably decreased and transporting ability thereby lessened.

ALLUVIUM. Any stream-deposited material.

ANEROID. A barometer whose changes are produced by the elasticity of the walls of a metal box containing a partial vacuum.

ANTECEDENT STREAM. Where local uplift occurs across the course of a river, the stream may erode down about as rapidly as the uplifted tract comes up. A youthful valley will result, in contrast with older portions both upstream and downstream. The stream is antecedent.

ANTI-TRADES. Winds above the trade winds, and blowing in the opposite direction.

ARTESIAN WELL. A well in which water rises above the level at which drilling encountered it. In many artesian wells, the water rises to the surface of the ground and flows continuously out of the well.

BADLANDS. Stream-dissected topography developed in regions of low rainfall, little vegetatioi, high gradients, and weak stratified rock. Characterized by steep bare slopes of closely spaced valleys, most of which are occupied by intermittent streams.

BAROGRAPH. An aneroid barometer with a recording pen attached to the vacuum box. A revolving drum, operated by clockwork, makes possible a continuous, automatic record.

BARRIER BEACH. A beach built off shore, enclosing a lagoon or marsh between it and the mainland.

BATHOLITH. A very large intrusion of igneous rock.

BAY BAR. A spit that has grown well out into, or even across, a bay.

BEDROCK. The consolidated rock generally covered by mantle rock or by deposits of unconsolidated material. Even if uncovered, it is usually termed bedrock.

BRAIDED COURSE. A stream occupying a flat-bottomed valley will, if it becomes overloaded, break out of banks as its channel fills and establish numerous dividing and uniting channel routes (braids) that continually shift position as aggradation goes on.

BUTTE. As used by most geologists, the term defines a flat-topped hill whose summit is held up by a horizontal layer of resistant rock.

CHRONOMETER. A very accurate clock.

CIRQUE. An amphitheatre-shaped valley head, generally due to erosion by a valley glacier.

CYCLE OF EROSION. The full sequence of erosional changes wrought by running water on a land surface. The end of the cycle theoretically comes when the land has been worn down so low that streams can no longer erode.

DEFLATION. Degradation of a land surface by the erosional action of the wind.

DEGRADATION. Lowering of a land surface by any or all of the erosional agents.

DELTA. The deposit made at the mouth of a stream on entering standing water.

DENDRITIC. Shaped like the branch and twig system of a tree, all members joining with acute angles between them.

DEPOSITION. Any agent of erosion may under certain conditions abandon part or all of its load. This is deposition. Compare with *aggradation*.

DETRITUS. Waste material produced by erosional agents. Soil and subsoil, river mud and gravel, dust and sand carried by the wind, glacial drift, beach sand and gravel, all are detritus, whether in transit or at rest.

DIASTROPHISM. All movements in the lithosphere.

DIKE. Intrusive igneous rock filling a vertical or nearly vertical crack in older rock.

DISTRIBUTARY. Stream courses which branch out *down* stream. Alluvial fans and deltas possess them. They result from channel filling which causes lateral escape of water and the formation of new channels, which in turn repeat the procedure. Thus distributary channels are continually shifting.

DOLDRUMS. The belt of calm air that lies over the "heat" equator.

DUNE. A hill built up by the accumulation of wind-transported sand.

ERRATIC. A fragment derived from bedrock that does not crop out in a particular drainage area. The stone therefore was transported either across the divide into the headwaters, or brought back up stream from the valley mouth. Glacial ice is generally responsible for the introduction of erratics into a region.

FAULT. A fracture in bedrock, along which displacement has occurred.

FINES. The sand, silt and clay part of the load carried by any transporting agency.

FIORD. A steep-walled glaciated coastal valley partly filled with sea water.

GEYSER. An intermittently eruptive hot spring.

GRADATION. The sum total of all processes which wear down higher places and fill up lower ones.

HACHURES. (1) Short lines attached at right angles to a closed contour on a map, indicating that the enclosed area is a depression without surface outlet. (2) Short lines drawn on a map as pictorial representations of the land slopes.

HOGBACK. A ridge determined by the outcropping edge of a tilted layer of resistant rock.

HORSE LATITUDES. The belt of calms at about 30° north, and south, of the equator.

HYDROSPHERE. The oceans, and all land water.

IGNEOUS. Produced as a result of volcanic forces.

INTERFLUVE. A region between streams; the divide and its slopes.

INTRUSION. (1) The entrance of liquefied rock into solidified rock. (2) A mass of the once-liquid rock, now cooled and solidified beneath the surface of the earth.

JUVENILE WATER. Water which presumably never before has been at the earth's surface. Volcanic steam comes largely from juvenile water.

KETTLE HOLE. A closed depression of appropriate proportions in morainic topography. Irregular deposition may cause them, also the melting of ice blocks buried in the glacial drift.

LACCOLITH. An igneous intrusion which has lifted the overlying rocks in the form of a dome.

LAVA. Igneous rock that has been extruded in liquid form on the surface.

LITHOSPHERE. The outer part of the solid earth.

LOESS. A fine-grained deposit, generally without stratification, that has accumulated by settling of dust from the air.

MAGMA. Liquid igneous rock material beneath the earth's surface.

MANTLE ROCK. The cover of detritus overlying the bedrock.

MEANDERS. Large curving loops in the course of a low-gradient stream.

MESA. A table-topped upland, larger than a butte, the summit flat determined by a layer of resistant rock.

METAMORPHISM. The process by which rock may become crystallized or re-crystallized under heat and pressure.

MONSOON. A wind that blows landward in summer, seaward in winter.

MORAINE. A deposit of glacially transported debris left by the melting of the ice.

NARROWS. Any unusual constriction of the width and steepening of the walls of a stream valley.

NATURAL LEVEE. A low broad ridge of alluvium margining a stream channel.

OFFSHORE BAR. A broad low submerged ridge composed of wave-transported detritus, and generally lying parallel with the shore line.

OUTWASH. Material transported and deposited by streams from melting glacial ice.

PALEOGEOGRAPHY. The delineation of lands and seas of the geologic past.

PENEPLAIN. The worn-down land of low relief late in the cycle of erosion.

PHOTIC ZONE. That upper part of the ocean water which light penetrates.

PLANETARY WINDS. The general atmospheric circulation of the earth. It includes the trade winds, anti-trades, prevailing westerlies, and the belts of calms called doldrums and horse latitudes.

PLUCKING. Pulling loose of rock fragments, chiefly by glacial ice.

PREVAILING WESTERLIES. The winds of the planetary system which blow northeasterly out of the northern horse latitude belt and southeasterly out of the southern horse latitude belt.

Progradation. The building out of the land into shallow coastal water.

Pumice. A finely porous volcanic rock. Essentially a solidified lava froth.

Rejuvenation. Because of uplift of the land, streams in maturity or old age may secure increased gradients and start downcutting again. This rejuvenation is recorded by a youthful narrow valley eroded in the bottom of the older valley.

Retrogradation. Destruction of coastal land by wave erosion.

Sea breeze. A daytime wind that blows from the sea toward and over the near-by land.

Sea Cliff. The cliff which is made by wave erosion on fairly high coastal land.

Sedimentary. Produced by the deposition of rock particles from a transporting medium.

Sill. An intrusion of igneous rock along a bedding plane of older sedimentary rock.

Sink. A topographic depression resulting from solution of limestone by ground water. Basin-like forms are most common. Well-like sinks are due to collapse of part of a cavern roof.

Spit. A bar built diagonally out from the shore, generally pointing back toward a more protected part of a bay.

Stalactite. An "icicle" of stone, grown down from a cavern roof through deposition of limestone by dripping water.

Stalagmite. The reverse of a stalactite. Deposition occurs on the floor and the growth is upward.

Stratosphere. That part of the atmosphere immediately above the cloud-bearing, dust-laden, and turbulent lower air.

Talus. The accumulation of rock fragments at the foot of a cliff.

Thermodynamic. Caused or operated by force due to the application of heat.

Tornado. An intensely vigorous storm whose circulation is spirally inward and upward.

Trade winds. Those planetary winds which blow equatorward in both hemispheres from the horse latitude calms toward the doldrum calms.

Travertine. Limestone deposited from ground water, generally on the floor of a cavern.

Trellis drainage. A pattern of right-angled stream courses determined by the "grain" of folded stratified rock. Narrows occur where streams cut through ridges made by edges of harder strata.

Tropical Cyclone. A very large whirling storm, of marked intensity, originating at certain seasons over tropical oceans and traveling into higher latitudes.

Troposphere. The lower turbulent part of the atmosphere, in which occur all clouds and dust.

Turbulence. A type of circulation marked by many constantly changing cross currents of varying velocities.

UNCONFORMITY. A "break" in a vertical sequence of rocks, recording an interval of erosion, instead of deposition. Essentially a buried land surface.

UNDERTOW. The return of water beneath waves breaking on a beach.

VARVE. Two seasonal layers recording a year of deposition.

WATER GAP. A narrows; that part of a stream valley cut through more resistant rock than encountered both upstream and downstream.

WATER TABLE. The upper limit of saturated ground.

WAVE-BUILT BENCHES. An offshore submerged terrace deposit composed of wave-handled debris.

WAVE-CUT BENCH. The terrace eroded beneath the waves at the foot of a sea cliff.

INDEX